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Static tension tests of long riveted joints

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STATIC TENSION TESTS
OF LONG RIVETED JOINTS

by

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SYNOPSIS

This paper is a report of an experimental and theoretical study of three long butt joints fabricated with A-7 steel and connected with 7/8" A 141 rivets. Rivet shear areas were proportioned using a tension-shear ratio of 1/0.75. Joint length was the major variable. The results of these tests are compared with previous tests of riveted and bolted connections. The data covers unbuttoning and slip characteristics of the connections and also the partition of load among rivet fasteners.

1. INTRODUCTION

1.1 Background and Purpose.

Consider a structural joint with several fasteners in line. As the structural joint is loaded, the end fasteners are more highly stressed. It can be shown theoretically and verified experimentally that as the connection increases in length the end fasteners carry a higher percentage of the load. When the end fasteners deform they affect a redistribution of load among the other fasteners. The amount of redistribution is a function of the fasteners' ability (ductility) to deform without fracture.

If the end fasteners lack ductility the joint experiences "premature" failure. The "premature" failure has been termed "unbuttoning" since failures begin at the ends and proceed toward the center of the joint as one would unbutton a shirt. A convenient way of portraying this effect of joint length on the ultimate strength of a connection was by the use of the non-dimensional unbuttoning factor, U[1]. It is expressed by the following equation:

$$U = \tau_{avg} / \tau_1$$

Where $\tau_{avg.}$ is defined as the average nominal shear stress at the time the first rivet fails and τ_1 is the average shear strength of a single rivet of the same lot. As joints become longer, the average nominal shear stress and the unbuttoning factor becomes smaller, since the fasteners are less successful in affecting a redistribution of the load.

Unbuttoning has been noticed in long riveted and bolted joints. The principle American reference on large riveted joints is the Davis, Woodruff and Davis report of 1940(2). Their tests show the unbuttoning trend but the joint configuration raises some question as to the influence of other variables. Because of these variables it is difficult to compare the unbuttoning phenomena for bolted and riveted joints. The comparison between bolted and riveted joints is desirable to indicate whether or not unbuttoning is more or less critical in long bolted joints than in long riveted joints. The absence of this comparison led to the omission of a discussion, of unbuttoning for the A325 bolt, from the Commentary of the 1960 Specifications for the Design, Fabrication and Erection of

Structural Steel for Buildings. Also absent from the 1960 Specifications is mention of the use of a reduced nominal shear stress for rivets in a long riveted joint. The purpose of the tests reported herein was to enable a direct comparison to be made on the unbuttoning phenomena for bolted and riveted joints and to determine how the unbuttoning factor would be affected by increasing the lengths of riveted joints.

In June of 1960 a dissertation[3] was presented describing a theoretical solution of the ultimate strength of bolted connections. With some modifications, it was shown[4] that this method could also be used for riveted joints. Theoretical results were obtained for the three long riveted joints included in this report and were compared with the actual test results to get an indication of the validity of the theoretical solution.

In the design of structural connections it has always been assumed that each fastener takes an equal share of the load. By the use of the semi-graphical theoretical analysis in Ref. 3, bolt forces were represented as a percentage of the equally distributed bolt force and demonstrate the amount of error in this common assumption. The ductility of a rivet is somewhat greater than that of the high strength bolt and therefore would seem to be able to redistribute the loads on the rivets more effectively. Results of the tests for this report provided data which could be used to determine this increased ductility in a rivet and its effect on redistribution of rivet forces.

1.2 Scope.

This report represents a fourth series of long joints included in the testing program on "Large Bolted Joints" conducted at Fritz Engineering Laboratory, Lehigh University. The tests, designated DR Series, were designed to determine the effects of joint length, unbuttoning, redistribution of rivet forces, and ductility in riveted joints. The DR Series consisted of three joints having from seven, ten, and thirteen rivets in each of two lines. The width was varied to conform to a T/S ratio of 1/0.75 which is used for balanced design in short riveted connections. All the joints were completely instrumented to provide data on unbuttoning, slip and partition of load. A literature survey is included and the results from some of these past tests are used to correlate the material submitted in this paper.

2. REVIEW OF LITERATURE

In reviewing the literature related to the static strength of riveted joints, a very small percentage were found to be related to the work presented in this paper.

Shortly after steel was introduced as a material of construction in 1867 J. W. Schwelder[5] pointed out that even in small triple riveted lap joints, all the rivets do not take an equal share of the load. Other papers written in the 19th century by J. T. Milton[6], The Watertown Arsenal,[7] and Carl Bach[8] caution the use of customary methods of application at that time, for determining loads of riveted joints. They mention that joints with multiple rivet rows do not have the same resistance per rivet as single row joints. This is attributed to unequal distribution of forces amongst the rivet rows and to the elastic deformation of plate material. After the turn of the century, W. H. Boughton[9] in the United States, presented a paper in which he also drew attention to the unequal distribution of forces over the rivets, but he maintained that the usual procedure of calculations was good enough because it was safe enough. All these papers, however, included work on very small joints and at loads within the elastic behavior of a connection.

The first theoretical study of load partition in steel rivets on a double shear type of plate splice under a static axial load was published in 1909. Ivan Arnolevic (10), in Austria considered the joint as a statically indeterminate elastic structure. In his explanation of joint behavior he dealt only with the elastic range. He related the plate and rivet deformations and developed equations which gave the load carried by each rivet. His conclusions are general in nature but two are of particular importance. First he concludes that rivet pitch in the direction of the axis of the joint should be as small as possible; secondly, that more than five rivets in any one line parallel to the axis of the joint are useless. In other words little is gained by adding more than 5 rivets since each inner rivet receives a lesser and lesser portion of the load and that those near the middle are practically idle.

In 1916 another theoretical analysis, on the load partition in the elastic range, was derived by means of the principle of least work by Professor Cyril Batho[11]. Also he performed very careful experiments to prove that the actual distribution was in very good agreement with his theoretical deductions. The equations he derived express the load carried by each rivet, from which it appears that the first and last row carry the major part of the total load (often up to 80 percent and more). Professor Batho's results, although obtained in a totally different way, agree well with those of Arnolevic[10]. However, these theoretical explanations have dealt with the elastic range of joint behavior and as a result the conclusions drawn are not indicative of the ultimate strength of the connection.

It appears that the first investigation of the behavior and ultimate strength of large riveted joints under load were carried out by Commander E. L. Gayhart[12] in 1926. A discussion of Commander Gayhart's paper was presented by William Hovgaard[13]. In his discussion he points out that when these riveted joints failed due to the shearing of rivets that the load is fairly evenly distributed among all the rivets. Only at low stresses do the outer rivets carry a disproportionate part of the load. This was contrary to the generally accepted opinion of the previous tests that the outer row always carried the principal part of the load and that it is, therefore, erroneous to base the design on the total rivet area. It should be noted, however, that even though these joints were large riveted connections they can not be considered long riveted joints since the specimens included rivet patterns which did not exceed 4 rivets in line.

Undoubtedly, the most important paper, published up until 1940 was that on Tension Tests of Large Riveted Joints. It was presented in the 1940 ASCE Transactions by R. E. Davis, G. B. Woodruff, and H. E. Davis(2). Their report included the most elaborate tests of large-size riveted joints that had been carried out to that time. In this paper they reported instances in which premature fastener failure had occurred in joints using 7/8" rivets. It was pointed out that this type of rivet failure occurs more frequently in longer joints and in those made with the more ductile steels. In general, they state that, "The test results indicate that the partition of stress among rivets is not uniform at any stage of loading, but in view of the probable inequalities of fabrication the usual design assumption of uniform partition is as reasonable as any that can be made".

In reply to this statement, Jonathen Jones[2] in his discussion states:

"It is gratifying that these tests should have led to this conclusion........Their record shows that this may be said of all of the rivets in any one joint. It is not so certain that it should be taken to mean that the same unit shear may be assumed for all of the rivets in a very long joint as for all of those in a very short one".

Jones' caution was appropriate and is evident when it is noticed that these investigators reported that the nominal shear strength of a joint with 18 rows of rivets was only 90% of the nominal shear strength of a 6 row joint.

The most valuable bibliography including the work up to 1945 was that of A. E. Richard de Jonge[15]. In 1945 he published "Riveted Joints: A Critical Review of the Literature Covering Their Department." Approximately 1200 items were reviewed and as such is an invaluable aid to the research worker.

After World War II, a paper presenting experimental and theoretical solutions for joints made of aluminum plate and connected with aluminum or steel rivets was published in 1953 by Professor A. J. Francis[16]. Though dealing with aluminum he presents solutions for the elastic and inelastic range and shows that the partition of load among the rows of rivets in an aluminum alloy double-shear riveted joint under static load is not uniform. He notes that in very long joints the load may not become uniformly distributed before failure, and there is a reduction in rivet performance. He showed that long joints suffer a loss in nominal shear strength of the fasteners from 15.5 to 23.6 percent of the strength of a single rivet. Also for reasons of economy, as well as of efficiency, as small a pitch as possible is desirable.

In 1959 E. Chesson Jr. and W. H. Munse[17], of the University of Illinois, presented a paper on the "Behavior of Large Riveted and Bolted Structural Connections". Although the arrangement of their rivet patterns were somewhat different than the ones presented herein, they show that unequal fastener deformations in long riveted joints produce lower average ultimate shear strengths than those obtained from single fasteners.

In the earlier phase of this study[18] joints were sectioned along the lines of rivets and the shear deformations measured. These deformations indicated that end fasteners deformed most and that deformations decreased toward the center of the joint. In summary, both of these papers bring out that the average nominal shear strength of the rivets are decreased by increasing the length of the joint.

3. DESCRIPTION OF TEST JOINTS.

3.1 DR-Series (Variable Width).

In the DR Series, joint length and width were the chief variables. Three test joints; one with two lines of seven rivets, another with two lines of ten rivets, and a third with two lines of thirteen rivets, each having a pitch distance of 3 1/2" and a grip of 4" were included in this series. (Fig. 1) The specimens were half of a double shear butt joint having outer lap plates of one inch thickness and having two one-inch plates combined to make up the inner main plates. The fasteners for each joint were 7/8" A 141 rivets chosen from AISC recommended lengths (21).

The design of the test specimens proceeded in the same manner as the design for the Long Bolted Joints conducted at Lehigh University except that a T/S ratio of 1/0.75 was used. For balance design the ultimate load of the net section of the plates must be equal to the ultimate load of the rivets.

$$P_{un} = P_{ur}$$

$$A_n \sigma_n = A_r \tau$$

$$\frac{\sigma_n}{\tau} = \frac{A_r}{A_n} = \frac{T}{S}$$

AISC specifications prescribe an allowable σ_n = 20 ksi and an allowable τ = 15 ksi.

$$\frac{T}{S} = \frac{\sigma_n}{\tau} = \frac{20}{15} = \frac{1}{0.75}$$

As n, the number of rivets in line, was varied from 7 to 13 the width (w) varied from 8.48 to 13.78 inches respectively. Figure 1 outlines the nominal dimensions for each specimen.

The specimen numbering system was as follows, the joint with 7 rivets in line was designated DR 71. The DR indicates the DR-Series of tests while the first number, 7, designates the number of rivets in line.

3.2 Material Properties.

3.2.1 Plates.

(a) STANDARD COUPON TESTS.

The plate material used for the DR Series was taken from five duplicate joints that were on hand at the Fritz Laboratory from the D Series - Part a tests. The material was ASTM A-7 structural steel cut from universal mill strips 24" x 1" and approximately 72'-0" long, and was supplied by the Bethlehem Steel Co. from its Sparrow's Point Plant. Detailed information concerning the cutting scheme used for test specimens and coupon material, along with a typical stress strain curve for the plate material and the results of all coupon properties can be found in Fritz Laboratory Report 271.8(1).

Summarizing the coupon tests it can be seen that the average static yield level stress was 28.4 ksi and the average yield stress was 28.5 ksi. These stresses were both lower than the ASTM yield point of 33 ksi while the mill test yield point was 37.5 ksi. The average ultimate tensile stress was 60.2 ksi which is a little higher than the ASTM minimum ultimate strength while the mill test report gave an ultimate tensile strength of 61.7 ksi. The variation between the mill report and the laboratory test results were, at first, attributed primarily to the difference in strain rate used in the mill and in the laboratory. However, since there was such a large difference, simulated mill tests were run to verify, if possible, the mill report's results.

The maximum allowable speed (strain rate) for tensile coupons set forth by the ASTM Standards is that at which the speed of the crosshead under load shall be adjusted so that its rate of travel will be not in excess of 1/16 inch per minute per inch of gage length. Three coupon tests were conducted at this rate. Three additional tests were conducted at a slightly greater speed to see if an even greater speed than allowed would affect the yield point stress. Table 1 summarizes these coupon tests along with the mill test and the standard ASTM tests for tensile coupons. It is obvious from these simulated mill tests that the speed of testing can not be considered as the primary reason for the variation in the yield point.

All coupons exhibited ductile type failures and hence with all the other properties given above would be called minimum strength A-7 steel.

(b) Plate Calibration.

In addition to the standard coupons, plate calibration coupons were made. The plate calibration specimens related the deformations of certain portions of a gage strip to a known tensile load. Plate calibration was accomplished by testing a duplicate section of one gage strip and the load-elongation behavior of one pitch length was recorded. The specimens were cut from the same material as that used in the prototype connections and had the same dimensions of plate thickness, pitch, gage length, and hole diameters as the prototypes. The dimensions and average curves of the plate calibration specimens are given in Figure 2.

3.2.2 Rivets.

(a) Standard Coupon Tests.

The rivets used in the DR Series were 7/8" diam. ASTM A141 rivets with a high button head and straight shank. They were supplied by the Bethlehem Steel Company from its plant in Lebanon Pennsylvania. The rivets for these tests specimens were chosen from AISC recommended lengths[21]. For a 4" grip, a rivet length of 6" under head was specified.

However, the rivet length that is actually required with well fitted plates is much less (about 5 3/8" or 5 1/2" for a 4" grip). The rivets used had to be cut down with a cold saw in the shop. Standard coupons[(19)] (0.505" diameter), cut from undriven rivets of the same lot as those used in the DR Series Joints, were tested in a 120 kip mechanical screw type testing machine. Table 2 lists the rivet properties. A typical stress-strain curve is shown in Figure 3. The automatic strain recorder was used during the early stages of the test. The strain rate was 0.01 in/min while the electric strain pickup and automatic recorder were in use. When the strain pickup was removed the rate was increased to 0.1 in/min and strain measurements were taken with dividers. Examination of the test results indicates that the laboratory value of yield stress (36.1 ksi) is somewhat lower than the mill report yield point (40.5 ksi). The average ultimate tensile stress was 57,670 ksi while the mill reported an average of 56,400 ksi.

(b) Shear Calibration.

Tests to determine the basic shear strength of single rivets were also conducted. To duplicate conditions in the joints a rivet was placed in a shear jig which subjected the rivet to double shear. The shear jigs were also riveted with the same pneumatic press that was used for the full size specimens. Shear tests of single rivets indicated an average value of ultimate shear ~~stress equal~~ to 55.3 ksi. The average curve of the results of the DR Series rivets is plotted in Figure 4.

3.3 Fabrication of Test Joints.

3.3.1 Shop Procedure.

The joints for the DR Series were originally fabricated for further tests of bolted connections. A description of the fabrication of the bolted joints is given in Ref. 1. Three joints (D52, D72, D92) were returned to Bethlehem Steel Company's fabrication shop in Bethlehem, Pennsylvania so that extra holes could be drilled, which would change the Tension-Shear ratio to approximately 1/0.75, and riveting.

The modifications that were made included drilling of four extra holes in specimen D52, six in specimen D72, and 8 in specimen D92 to convert them to riveted joints DR71, DR101, and DR131 respectively. Measurements were also made to determine the amount of hole misalignment due to the additional drilling.

The misalignment was not considered severe in any of the specimens.

All the specimens were riveted according to standard shop riveting practice. The plates were fastened in position with four pins in the corner holes to hold the joint in alignment. The rivets were heated in an electrical induction heater and riveted with a pneumatic press (bull).

Through a misunderstanding in the detail drawings of the D Series - Part a tests, a mechanical grinder was used to remove all the mill scale from the plates. The faying surfaces were completely devoid of mill scale and quite shiny and reflective.

3.4 Instrumentation.

The following equipment was used to instrument and measure deformations of the test specimens:

(1) Electric strain gages (SR-4) for measuring strains in the inner and outer plates;

(2) Slide extensometer for measuring plate elongations between each transverse row of rivets;

(3) Dial gages (0.001") for measuring slip between the inner and outer plates as well as total elongation of the joint.

(4) Dial gages (0.0001") for measuring relative displacement between the plies of material making up the outer and inner plates.

In the DR Series, the instrumentation of every joint was similar. Figure 5 shows a schematic of the instrumentation used for all joints. A more detailed description on the instrumentation of the test joints may be found in Ref. 1.

4. TEST PROCEDURE.

The riveted joints were tested to failure in the 5,000,000 lb. hydraulic testing machine. Figure 6 shows a test specimen in the testing machine. The test procedure was standardized so that each joint was tested under identical conditions.

Precautions were taken in aligning the specimen when it was mounted in the testing machine. The specimen was then fitted with the gages and dials shown in Figure 6.

Prior to the application of load, zero or "no-load" readings of all dials and gages were taken. The specimen was then gripped and an initial load of 100 kips applied, after which all readings were taken. Load was applied in 100 kip increments thereafter. Readings of all dials and gages were taken at each load increment. Overall elongation dials and slip dials were also read at each 50 kip increment as the specimen was loaded. This procedure was followed until major slip occurred.

At major slip, the testing machine would drop load due to the sudden displacement and stabilize at some lower load level; overall elongation readings and slip dials were read prior to major slip and after the load had stabilized at its lower level. Load was again applied in 100 kip increments to slip load and beyond. After the plates had yielded the loading valve of the testing machine was closed at each 100 kip increment and no readings were taken until the load had stabilized. When evidence of straining had stopped, all readings were taken. After the first 100 kip increment beyond plate yield the specimen was partially enclosed with a wire cage as a safety precaution. This 100 kip increment procedure was followed until failure.

Overall elongation dials that were expected to run out were reset during testing. Slip dials which ran out prior to failure were removed from the specimen. All SR-4 strain gages were read where possible.

When shearing of a rivet occurred it was followed by a drop in load in the testing machine. However, it was not always evident that a rivet had sheared if it did not fly out of the specimen. In such a case, if a "pinging" sound was accompanied by a drop in load, the unloading valve of the machine was opened to arrest the possible failure at this point. After the load had dropped to a safe level, the joint was inspected to see if a rivet had sheared. If failure had occurred all readings were then taken. If the specimen had not unbuttoned, load was again applied to the point of failure following the same procedure as before.

5. TEST RESULTS.

A complete summary of the test results is given in Table 3. The specimens failed by the shearing of one or two end rivets which was accompanied by a substantial drop of load. The load at which the first rivet sheared has been considered the ultimate load for the joint. A discussion of each test follows:

The smallest joint DR71, experienced first major slip at a load of 444 kips. This corresponded to an average rivet shear stress of 26.4 ksi. However, it should be noted that a few minor slips occurred before and after major slip. When the load reached 738 kips a noise similar to that experienced at the slip load was heard. This load corresponded to an average shear stress of 43.9 ksi. A drop in load occurred and the loading valve on the testing machine was closed. Investigation disclosed that the top rivet in the north row (Fig. 7) had sheared off at the manufactured head and could be removed after the load had stabilized at 680 kips.

Joint DR 101 slipped at a load of 518 kips or an average rivet shear stress of 21.6 ksi. As additional load increments were applied, periodic noises, sounding like a scraping or grating of the plate surfaces were noted. This was accompanied by a decrease of 2 to 5 kips in the load. Apparently further slippage was occuring. Due to the artificial condition of dropping load created by the testing machine (in an actual structure the load would remain constant) the specimens were not forced to slip into full bearing at the major slip load, but experienced instead a partial slip. Failure occurred at a load of 942 kips. The corresponding average rivet shear stress was 39.2 ksi. After the load had stabilized and it was safe to investigate the specimen, it was seen that both top rivets had sheared. (Fig. 8). Figure 9 shows the load-elongation relationship for joint DR 101.

The largest specimen, DR 131 experienced major slip at a load of 830 kips. The nominal rivet shear stress was 26.6 ksi. A few small slips also occurred before and after major slip. At a load of 1216 kips a loud noise was heard which was followed by a drop in load. The nominal rivet shear stress was 38.9 ksi. After the load had stabilized the specimen was investigated. At this time, one could not pull out or rotate any of the rivets so it was assumed the specimen had not failed. The specimen was again loaded. When a load of 1210 kips was reached (6 kips lower than the previous maximum load of 1216 kips) another loud noise with a corresponding load drop occurred. After examining the specimen again it was seen that the top north rivet had sheared. Figure 10 shows an overall picture of DR 131 after rivet failure.

6. THEORETICAL SOLUTION

6.1 Origin and Development of Theoretical Solution.

In Reference 3 a method of determining the unequal distribution of load among bolts of a double shear splice under static axial load and also a prediction of the ultimate strength of the connection has been developed. It has been shown[4] that with modifications, the semi-graphical analysis described in Reference 3 can be applied to riveted joints. The forces acting on each rivet can be found by the solution of an equilibrium equation and a set of compatibility equations. The non-linear relationships of force to deformation can be determined experimentally by tests of representative portions of plate and of single rivets. This solution can also be used to predict the ultimate strength of rivets in balanced design.

The following discussion describes the theoretical analysis and results of the DR Series and compares them with the actual results. Also included is a theoretical analysis of four hypothetical riveted connections to study the effect of varying the pitch in a riveted joint. For a complete description of the theoretical solutions see References 3 and 4.

6.2 Calibration Procedures.

(a) Rivet Shear Calibration.

The purpose of the rivet shear calibration was to relate the deformations of a single rivet to known values of applied load. The rivets being calibrated must have the same dimensions, basic properties, and heat treatment as those used in a prototype joint. A single hole connection is used to calibrate the rivet and is called a shear jig. It must be made of the same material as that of the prototype joing in order that the bearing deformations will be similar. The shear jig was loaded in a testing machine and corresponding deformations were determined. The average curve of the results of the DR Series rivets is plotted in Figure 4. This curve provides the relationship between the rivet offset and load, rivet offset occuring when the inner and outer plates move with respect to one another. When this takes place the hole reference points are misaligned by an amount called the hole offset, Δ. For a complete explanation of the test procedure see References 3 and 20.

(b) Plate Calibration.

The purpose of the plate calibration was to relate the deformations of certain portions of a gage strip to known tensile loads. The plate calibration specimens should be fabricated from the same material as that used in the prototype connection and has the same dimensions of plate thickness, pitch, gage length, and hole diameters as the prototype. Plate calibration is accomplished by testing a duplicate section of one gage strip and recording the load-elongation behavior of one pitch length. The dimension and average curves of the plate calibration specimens are given in Figure 2.

Knowing the load-deformation relationships for plates and rivets, the solution of the compatibility and equilibrium equations can be made by a graphical trial and error solution of forces within the hypothetical joint. Illustrations of this method are given in References 3 and 4.

6.3 Results.

A summary comparing the theoretical and experimental results is given in Table 4. Both the ultimate strength and the unbuttoning factor are compared. In joints DR 71, DR 101, and DR 131, the errors were +0.27, +2.55 and -1.64% respectively. The correlation between the predicted ultimate strength and the actual failure load supports the validity of the theoretical analysis.

The effect of varying the pitch in a riveted joint was investigated in Reference 4. Using the theoretical analysis four hypothetical riveted joints each having thirteen rivets in line, were analyzed. The calibration specimens upon which the analysis was based had the same physical and mechanical properties as the DR Series test connections. Table 5 gives the pitch, overall length, theoretical ultimate load, and the unbuttoning factor for the hypothetical joints. The results show clearly that increasing the pitch causes a substantial reduction in ultimate strength. A reduction of 13.8% resulted when increasing the pitch from 2 1/2" to 6". To gain a further insight of the effect of the pitch on joint efficiency the unbuttoning curve in Figure 11 is shown. It is seen that for a riveted joint with a given number of fasteners the unbuttoning factor also decreases when increasing the pitch.

Other investigators[10, 16] have also noticed this reduction in strength when rivet pitch is increased and have concluded in their reports that the pitch distance should be kept to a minimum.

7. ANALYSIS OF RESULTS.

7.1 Unbuttoning Factor.

When the end fasteners of a structural connection fail prematurely, and the rest of the joint remains intact, a term called the unbuttoning factor has been used to define this type of failure. The unbuttoning factor "U" has been defined (Section 1) as the ratio between the average nominal shear stress at the time the first fastener fails to the shear strength of a single fastener of the same lot.

This type of failure usually occurs at the free end of the lap plates. In Figure 12 the free end of the lap plates is shown. In addition to the shear deformation in the fasteners an axial deformation also takes place which results from the tendency of the lap plates at the free end to bend out. When this occurs the lap plates place tension on the outer fasteners adding to their fracture deformation. At the other end of the specimen the continuity of the lap plates prevents outward movement of the plates and hence little or no additional axial deformation in the end fasters takes place. This phenomena which causes the free ends of the lap plates to bend out is only a secondary effect since shearing of the rivets is by far the most important item which causes fracture deformation. However, when unbuttoning occurs in a structural joint, this secondary effect undoubtedly causes the end fasteners to shear more frequently at the free end of the lap plates.

In Figure 13 the non-dimensional unbuttoning factor "U" is plotted as a function of joint length and the number of 3 1/2" pitches. The figure shows excellent correlation between the predicted and the actual values of the DR Series. It is apparent that as joint length increases the unbuttoning factor decreases. In other words the average shear stress of rivets in joint DR 71 was 84% of the shear stress of a single rivet as compared to 74% in joint DR 131.

In previous work length has effected the ultimate strength of a joint connected either by rivets or bolts. In Figure 14, the unbuttoning curve for bolted joints[4] is compared with the results of the riveted joints. The same trend is noticed in the riveted joints as in the bolted connections but the rivets appear to be 3 to 12% more effective as measured by unbuttoning. The reason for this increase in efficiency in the riveted joints is due mainly to the redistribution of forces in the rivets which depends significantly upon the ductility of the fastener under shearing loads. However, it should be noted that the bolted joints took approximately 50% more load than identical riveted joints.

Figure 15 compares two series of tests (2, 16) on long riveted joints with those included in this report. This curve is similar to the unbuttoning curve except that τ_{avg}, the average nominal shear stress at the time the first fastener fails is plotted as the ordinate. The average shear strength of a single rivet, τ_1, was not obtained in the other series of tests. The absicssa is plotted as joint length. Although the previous tests had different rivet patterns, rivet diameters, and material properties, the average ultimate shear stress decreases with an increase in joint length. This is the same trend that occurs in the unbuttoning curve.

7.2 Joint Slip.

In bolted joints (14) the nominal coefficient of friction is calculated by use of the equation $u = F/N$ where "u" is the coefficient of friction, "F" is one half of the slip load (because the load is divided into two plates), and "N" is the average total clamping force for the bolt group. However, in riveted joints the average total clamping force can not be computed directly. When a hot driven rivet cools it contracts longitudinally as well as laterally. Due to this longtiduinal contraction, the rivet develops a residual tensile stress and clamps the gripped material. This clamping force is very unpredictable and can not be measured accurately. Since the clamping forces in riveted joints are so unpredictable the design assumption is justified in stating that no clamping force exists in riveted joints.

The slip characteristics of the DR Series test specimens can best be analyzed by comparing them with the D Series - Part a tests(1). The average slip coefficient noted in the testing of the DR Series - Part a joints was u = 0.28. Since the plate material for the DR Series and D Series - Part a was the same (Section 3), the faying surfaces can be considered equal and therefore u can be assumed equal to 0.28 for the DR Series tests. The riveted joints DR 71 and DR 101 slipped at loads which were approximately 120% and 95% respectively of those developed by the comparable bolted joints D71 and D 101. Joint DR 131 can not be compared since no joint with 13 bolts in line was tested in the D Series - Part a tests.

An estimate of the mean clamping force of the rivets in the DR Series joints can be made by use of the "slip coefficient"(22), where:

$$u\text{"slip"} = \frac{P\ slip}{mn\ \bar{T}i}$$

and u"slip" = slip coefficient

P slip = the load on the joint which causes it to slip.

m = the number of slip planes. In this case 2 for a double shear joint.

n = the number of rivets.

$\bar{T}i$ = the mean clamping force of the rivets.

By letting u"slip" = 0.28 and knowing the slip load (P slip) for each DR Series joint, mean clamping forces of the rivets for each joint can be computed. For joints DR 71, Dr 101, and DR 131, mean clamping forces of the rivets were 54.5 kips, 46.5 kips, and 57 kips respectively. These results clearly show that the clamping force for a rivet is quite unpredictable.

On cooling the rivet also contracts laterally, so that it does not completely fill the hole. The fact that a major slip occured in each of the DR Series joints shows that the rivets did not completely fill the holes as is usually stated.

7.3 Distribution and Ductility.

Figures 16 to 18 show graphically the dispersion of the theoretical rivet forces in each of the specimens as load is applied. It is evident that the end rivet reaches a maximum load and then falls off. When this occurs the other rivets carry the additional load which can be seen by the sharp increase in curvature near the ultimate load of the specimen. These rivets are taking advantage of the reserve ductility beyond ultimate of the end rivet. The amount of additional load these other rivets may take varies somewhat due to the material properties (ductility) of all the rivets and of the plate.

The ductile properties of a rivet under shearing load can be seen best by comparing a 7/8" diameter rivet with a 7/8" diameter structural A325 bolt. Figure 19 shows the average shear calibration curves of an A325 bolt and an A141 DR lot rivet. The tests were performed under identical conditions of strain rate. It can be seen that the deformation of the bolt at rupture load is almost equal to deformation at ultimate load. Since the change in elongation is so small it has been neglected in the theoretical solution for the ultimate strength of a bolted connection (Section 6). However, the deformation of the rivet changes substantially from ultimate load to rupture load and greatly affects the theoretical solution. The rivet is shown to deform approximately 20% more than the bolt after ultimate load. For this reason riveted connections can redistribute the loads of their fasteners more effectively than in bolted connections. This behavior, however, is very unpredictable and varies from rivet to rivet. Therefore in riveted joints ultimate strength predictions are more difficult.

In Figures 20 to 22 the dispersion of the theoretical rivet forces can be seen more clearly. The ordinate represents the applied load as a percentage of maximum gage load and the abscissa represents the rivet force as a percentage of the equally distributed rivet force. If all of the rivets shared an equal portion of the load all of the curves would be vertical lines at the abscissa 100. From inspection of these graphs, the shorter joint DR 71 shows that the partition of load among the rivets is more uniform. By this we mean that the concentration of the curves is in the vicinity of the 100%

abscissa. This trend is expected since in very short joints, where there are few rivets, the rivets do share the load equally.

The unequal rivet deformation and resulting inequality in the partition of load which caused the premature shear failures is evident when inspecting a sawed section of joint DR 71. Figure 23 shows a sawed section of joint DR 71 after the end rivet sheared. The sectioned connection reveals that the end rivets were the most highly deformed while the inner rivets had comparatively lower deformations. This verifies the results we obtained showing the unequal partition of load among the rivets at the ultimate load of the specimen. An enlarged view of the end rivet is shown in Figure 24. Other investigators[17, 18] have also used sections of their specimens to analyze the unequal partition of load among fasteners in a structural connection.

8. CONCLUSIONS

The following conclusions are based on test results of the DR Series tests conducted at Lehigh University and on results of previous work with riveted and bolted connections.

1. As joint length increases the average shear stress of the rivets in the connection decreases. The ratio of this average shear stress of all the rivets at failure to the ultimate shear strength of a single rivet is called the unbuttoning factor. In riveted joints (pitches of 3 1/2") the unbuttoning factor decreased from 0.84 in a 7 row riveted joint (total length, end rivet to end rivet = 21") to 0.74 in a 13 row riveted joint (total length = 42" Figure 13).

2. By modifying the semi-graphical analysis described in Reference 3, the theoretical ultimate strength of an axially loaded double-shear riveted plate splice can be predicted. The predicted theoretical ultimate strength shows good agreement with the results of tests. In the tests reported herein the difference between the predicted ultimate loads and the actual

ultimate loads ranged between +2.55% and -1.64%.

3. The theoretical analysis was used to determine the effect of fastener pitch on the ultimate strength of a connection. In a hypothetical thirteen rivet joint a change in pitch from 2 1/2" to 6" resulted in a drop in ultimate strength of 13.9% (Table 5 and Figure 11). Thus the ultimate strength of the fasteners in a connection depends not only on the number of fasteners but also on their spacing in the line of the load.

4. Slip occurred in all riveted joints, which were tested. Hence, the design assumption which states that the rivets completely fill the holes is not correct.

5. The riveted joints that were tested did not completely equalize load among the fasteners. Therefore, the design assumption which states that each rivet carried an equal share of the load is not correct. This can best be seen in Figures 20 to 22, which shows the rivet forces as a percentage of the equally distributed rivet force. It is obvious that as the length of a riveted joint increases the distribution among the fasteners becomes more unequal.

6. The ductile capacity of a structural rivet is somewhat greater than that of the A325 High Strength Bolt. The unbuttoning curve (Figure 14) points out that a riveted joint could be 3% to 12% more efficient than a bolted joint of equal length. However, bolted joints (4) take approximately 50% more load.

7. The results of this thesis could be used to revise the design procedure for long riveted joints. It could provide a design procedure in which the factor of safety against rupture of a long riveted joint would be the same as that for a short riveted joint.

9. NOMENCLATURE

Capital Letters

A_n	Area on net section of plate
A_r	Nominal shear area of rivets
L	Length of joint
N	Number of Pitches
P_G	Load on gage strip
P_{un}	Ultimate load on net section plate
P_{ur}	Ultimate load of the rivets
R	Rivet force
S	Average shear stress (in T/S ratio)
T	Tensile stress on net section (in T/S ratio)
U	Unbuttoning factor
W	Width of joint

Small Letters

e	Elongation of one pitch length of plate from one centerline to the next centerline of the hole
e'	Elongation of one pitch length of plate from one bearing side to the next bearing side of the hole

g/d_h — Expresses the ratio of gage (transverse spacing of rivet lines) to the actual diameter of the hole in the plate

n — Number of rivets in line

p — Pitch

t — Thickness

u — Coefficient of friction

<u>Greek Letters</u>

δ — Calibration rivet or bolt offset

Δ — Hole offset

τ — Nominal fastener shear stress or allowable shear stress

σ — Allowable tensile stress

10. TABLES AND FIGURES

NUMBER OF SPECIMENS	STRAIN RATE IN. MIN IN OF GAGE	YIELD POINT		ULTIMATE STRENGTH		% ELONGATION IN 8"	NOTES
		MEAN KSI	SS* KSI	MEAN KSI	SS KSI		
16	0.005	28.5	1.18	60.0	0.854	33.2	
3	0.0625	30.1	0.459	61.1	0.548	32.1	MAX ALLOW. STRAIN RATE A.S.T.M.
3	0.075	29.7	0.361	60.3	0.812	33.5	
—	—	37.5	—	61.7	—	28.0	MILL

*Standard Deviation

TABLE 1 SUMMARY OF COUPON TESTS, DR SERIES

COUPON NUMBER	STATIC YIELD POINT psi	YIELD POINT STRESS psi	ULTIMATE TENSILE STRESS psi	% ELONGATION IN 8" %	% REDUCTION IN AREA %
DR 1	33,250	36,500	57,500	39.5	58.6
DR 2	33,000	36,250	57,600	37.0	57.3
DR 3	32,750	35,500	57,900	40.0	57.0
AVG.	33,000	36,080	57,670	38.8	57.6
MILL		40,500	56,400	33.3	58.8

TABLE 2 RESULTS OF RIVET COUPON TESTS (7/8" RIVETS)

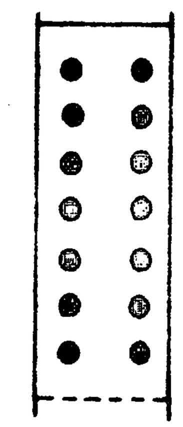
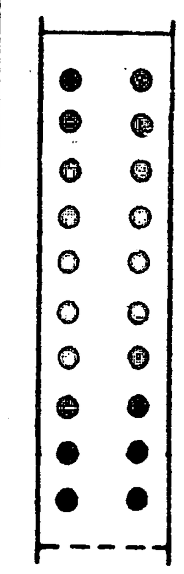
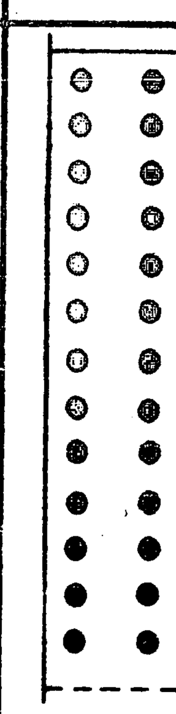
ITEM	UNITS	DR 71	DR 101	DR 131
PATTERN				
ALL holes drilled $\frac{15}{16}''$				
ALL pitches $3\frac{1}{2}''$				
Gage = $\frac{1}{2}''$				
RIVETS				
No. in line		7	10	13
No. of $\frac{7}{8}''$ A141 rivets		14	20	26
Nom. shear area	sq. in.	16.83	24.04	31.25
PLATES				
Nom. width	in.	8.48	11.12	13.78
Nom. thickness	in.	2	2	2
Nom. gross area	sq. in.	16.96	22.24	27.56
Nom. net area	sq. in.	13.21	18.49	23.81
Actual net area	sq. in.	13.18	18.47	23.73
% Deviation in net area	%	-0.21	-0.11	-0.34
T/S RATIO (A_S/A_N)				
Nominal		1:0.78	1:0.77	1:0.76
Actual		1:0.78	1:0.77	1:0.76
WORKING LOAD (T = 20,000; S = 15,000)	kips	252	361	469
SLIP LOAD (First Major)		444	518	830
Nom. rivet shear	ksi	26.4	21.6	26.6
Nom. tension, net section	ksi	33.6	28.0	34.9
TYPE OF FAILURE		rivet	rivet	rivet
Load at failure	kips	738	942	1216
Nom. rivet shear	ksi	43.9	39.2	38.9
Nom. tens. – net section	ksi	55.9	51.0	51.0
Act. tens. – net section	ksi	56.0	51.0	51.2
UNBUTTONING FACTOR				
U		0.836	0.747	0.741

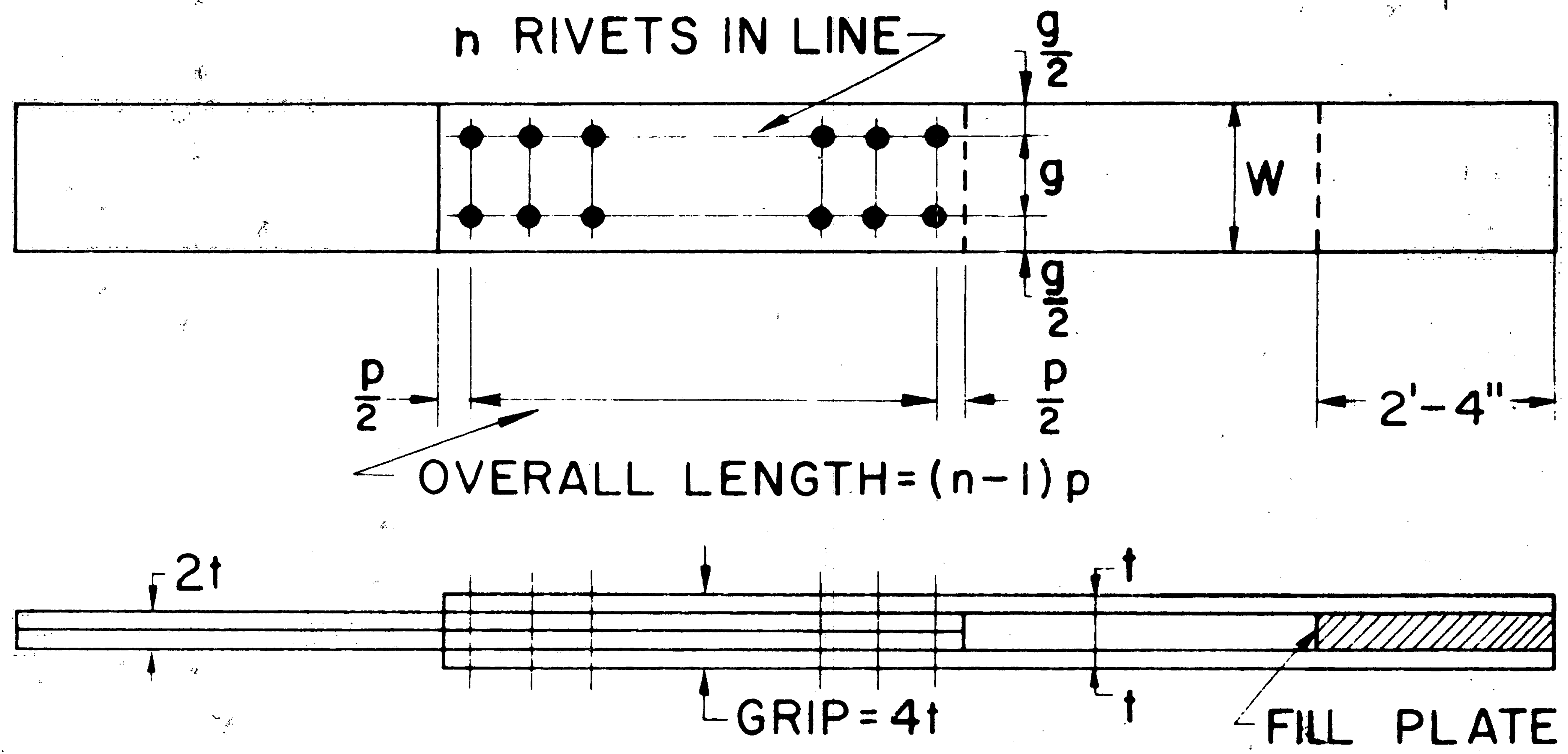
TABLE 3. RESULTS OF TESTS, DR-SERIES

SPECIMEN	ULTIMATE LOAD kips		% ERROR %	UNBUTTONING FACTOR U	
	THEORETICAL	TEST		THEORETICAL	TEST
DR 71	740	738	+0.27	0.838	0.836
DR 101	966	942	+2.55	0.765	0.747
DR 131	1196	1216	-1.64	0.729	0.741

TABLE 4 SUMMARY OF THEORETICAL AND TEST RESULTS

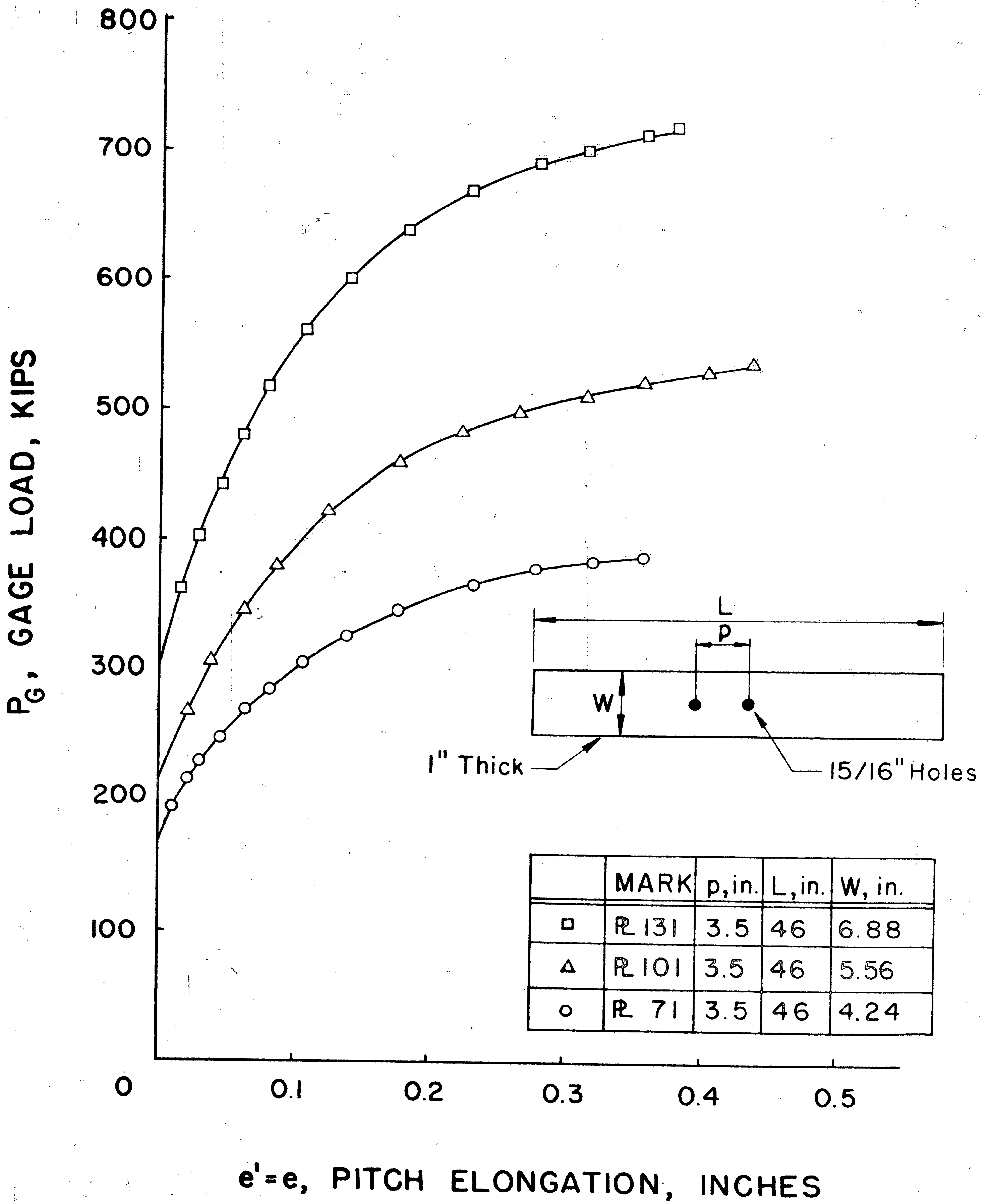
HYPOTHETICAL JOINT	NUMBER OF FASTENERS n	PITCH p in.	OVERALL LENGTH L in.	THEORETICAL ULTIMATE (P_G) kips	UNBUTTONING FACTOR U
PC9c-13DR	13	2 1/2	30.0	640	0.775
PC9b-13DR	13	3 1/2	42.0	598	0.724
PC9d-13DR	13	4 1/2	54.0	573	0.694
PC9e-13DR	13	6	66.0	552	0.669

TABLE 5 SUMMARY OF THEORETICAL RESULTS FOR A 13 ROW RIVETED CONNECTION



MARK	n	t	WIDTH IN.	GAGE IN.	g/d_h	$A_{riv.\,nom.}$ SQ. IN.	A_{net} SQ. IN.	$\frac{T}{S}$
DR71	7	2"	8.48	4.24	4.52	16.83	13.21	1:0.78
DR101	10	2"	11.12	5.56	5.94	24.04	18.49	1:0.77
DR131	13	2"	13.78	6.89	7.35	31.25	23.81	1:0.76

FIG. 1 DIMENSIONS OF JOINTS, DR SERIES



	MARK	p, in.	L, in.	W, in.
□	PL 131	3.5	46	6.88
△	PL 101	3.5	46	5.56
○	PL 71	3.5	46	4.24

FIG. 2. LOAD-ELONGATION RELATIONSHIPS OF PLATE CALIBRATION SPECIMENS

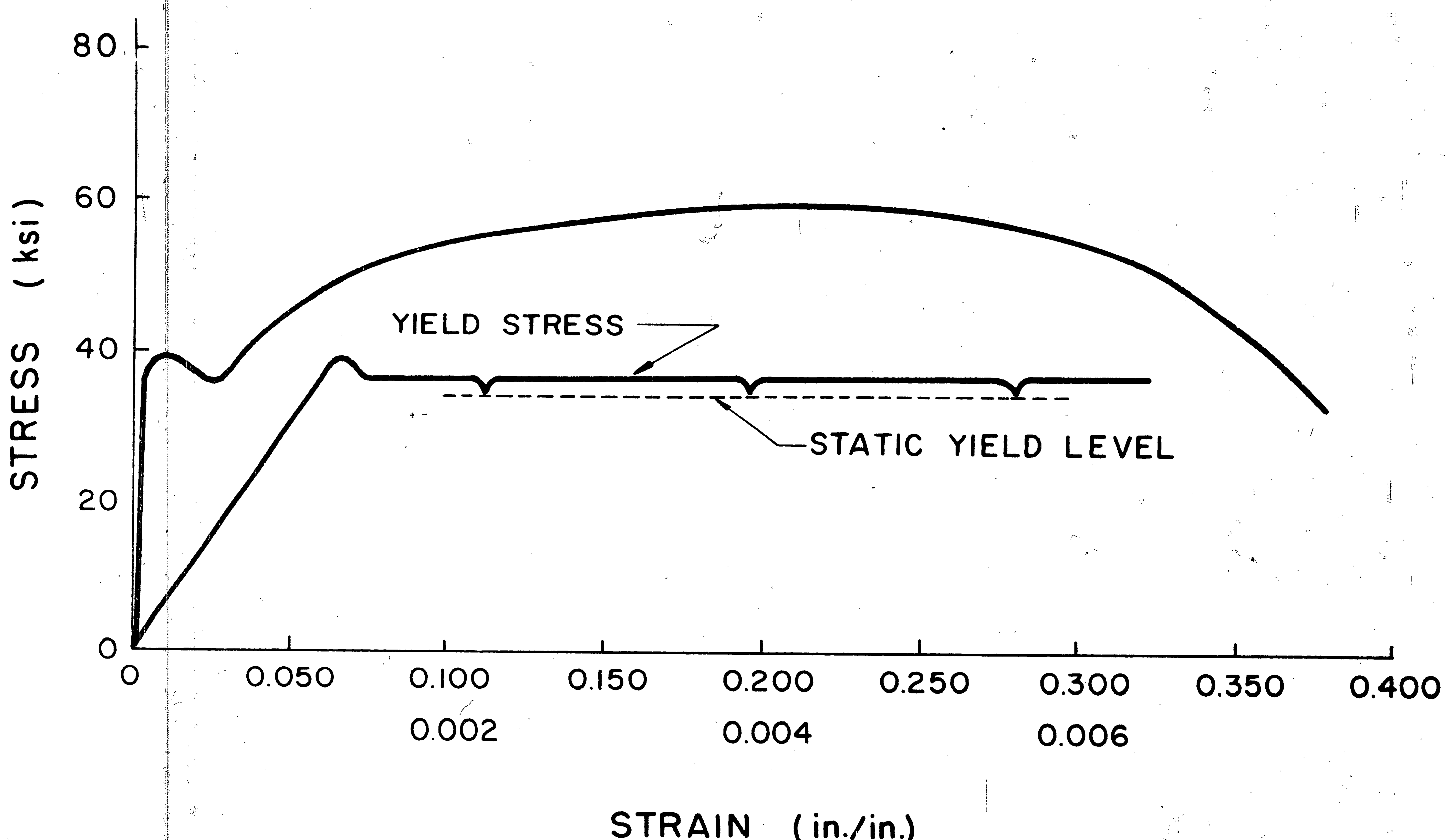


FIG. 3 STRESS-STRAIN DIAGRAM FOR RIVET COUPONS
(0.505" DIAMETER CUT FROM 7/8" MFG. RIVETS)

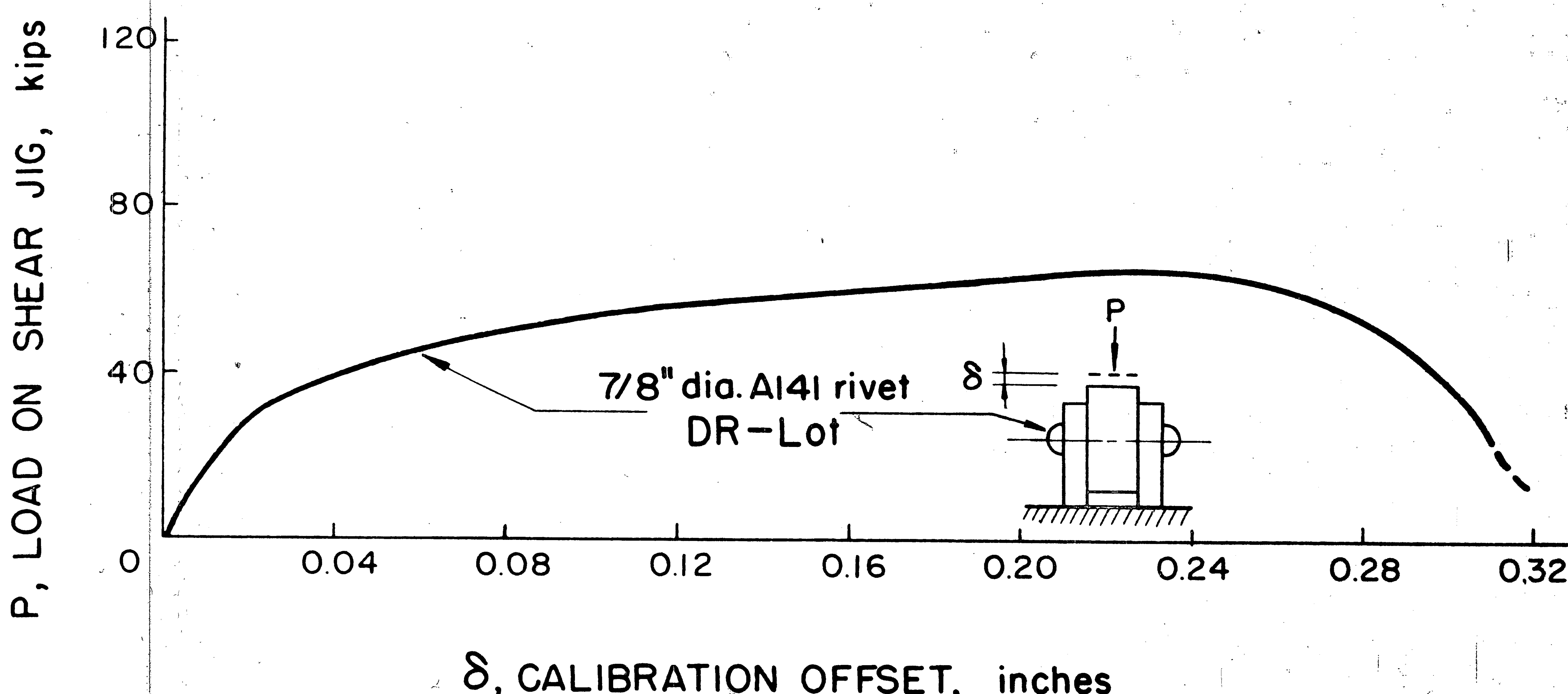


FIG. 4 AVERAGE RIVET SHEAR CALIBRATION CURVE

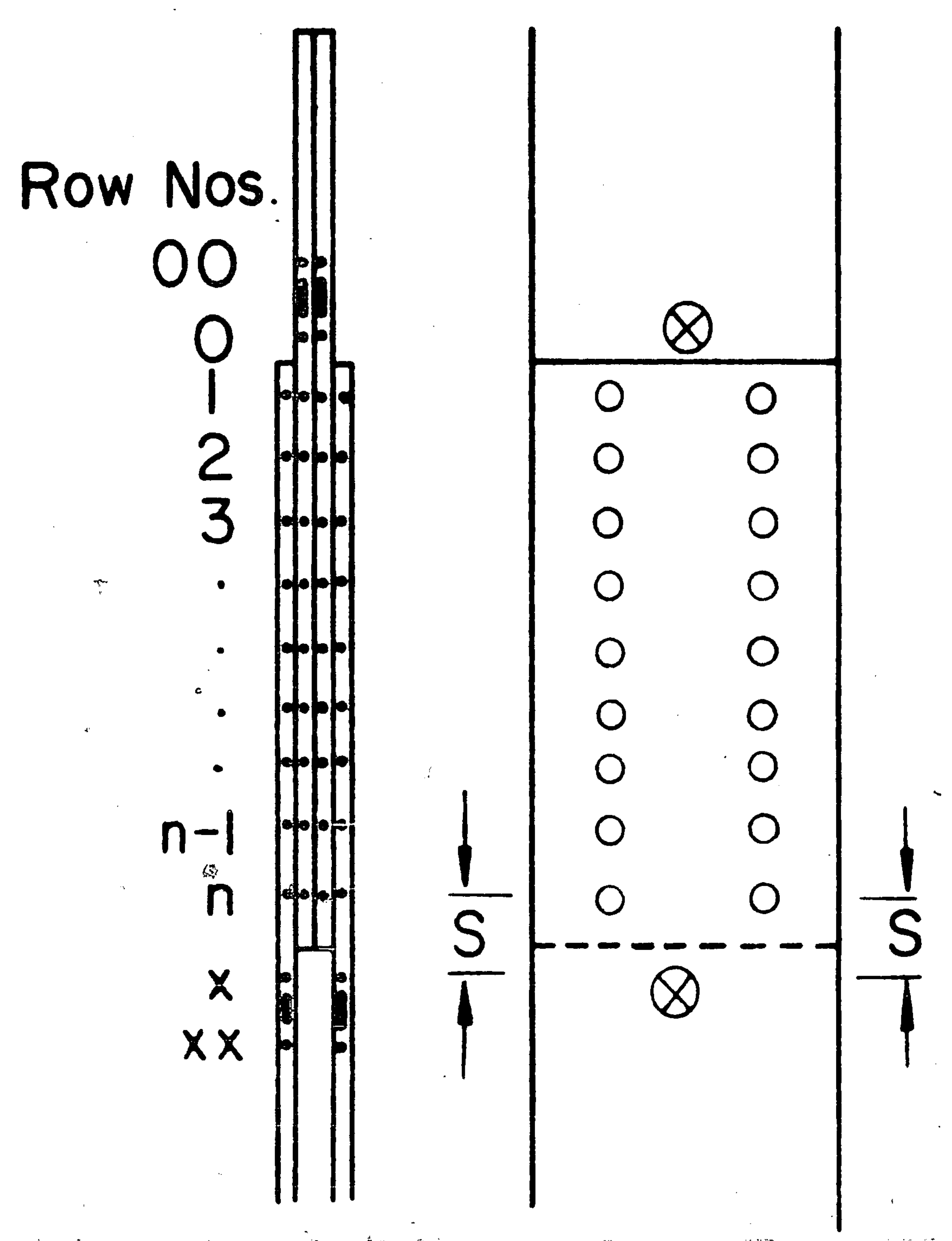
Key

S — location of slip gage

I — location of SR4, Type "A" gage

• — gage point for slide bar extensometer

⊗ — gage point for joint elongation gage



DR-SERIES

FIG. 5 INSTRUMENTATION LAYOUT

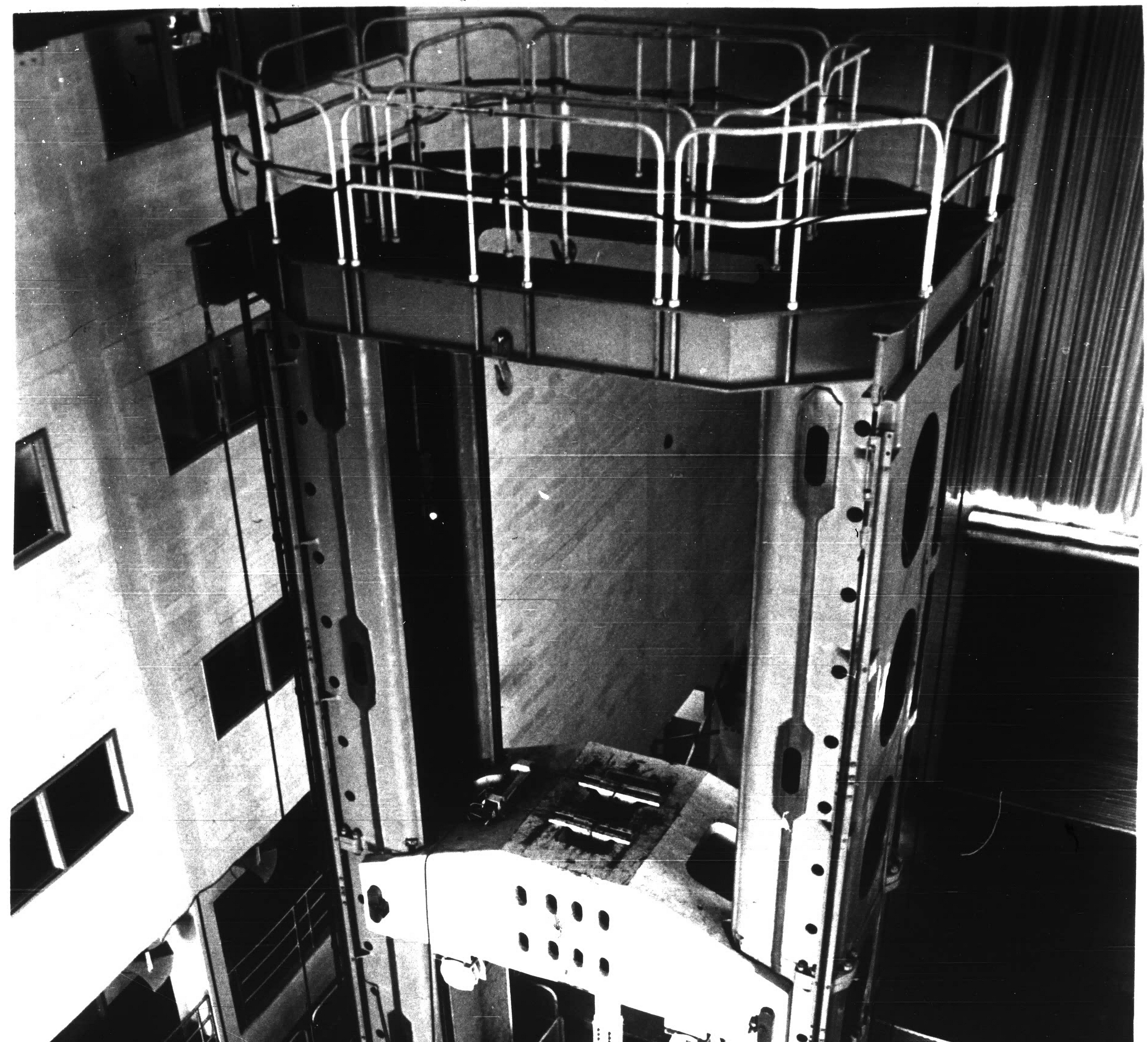


FIG. 6 TEST SPECIMEN IN 5,000,000 LB.
HYDRAULIC TESTING MACHINE

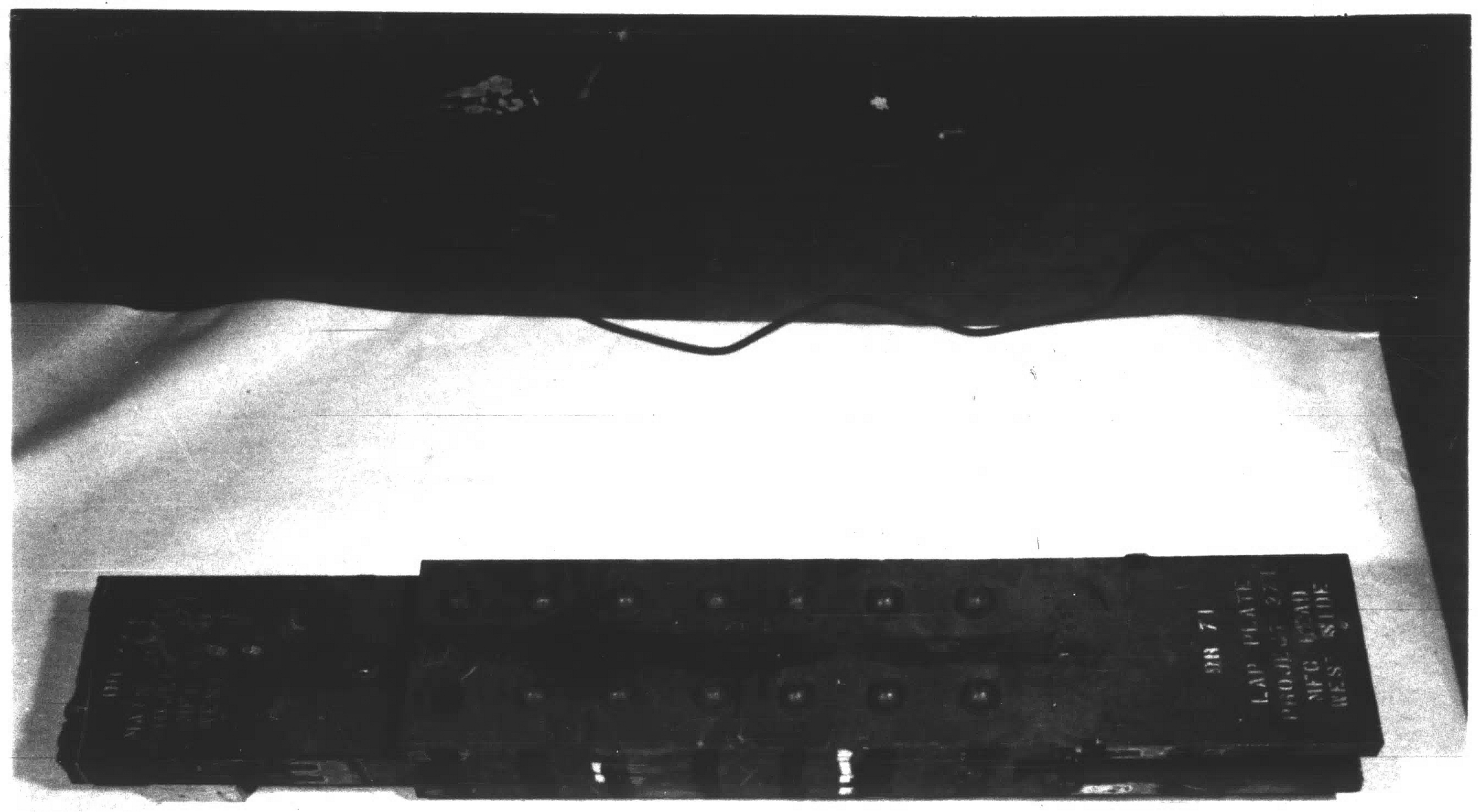


FIG. 7 JOINT DR 71 WITH TOP RIVET SHEARED

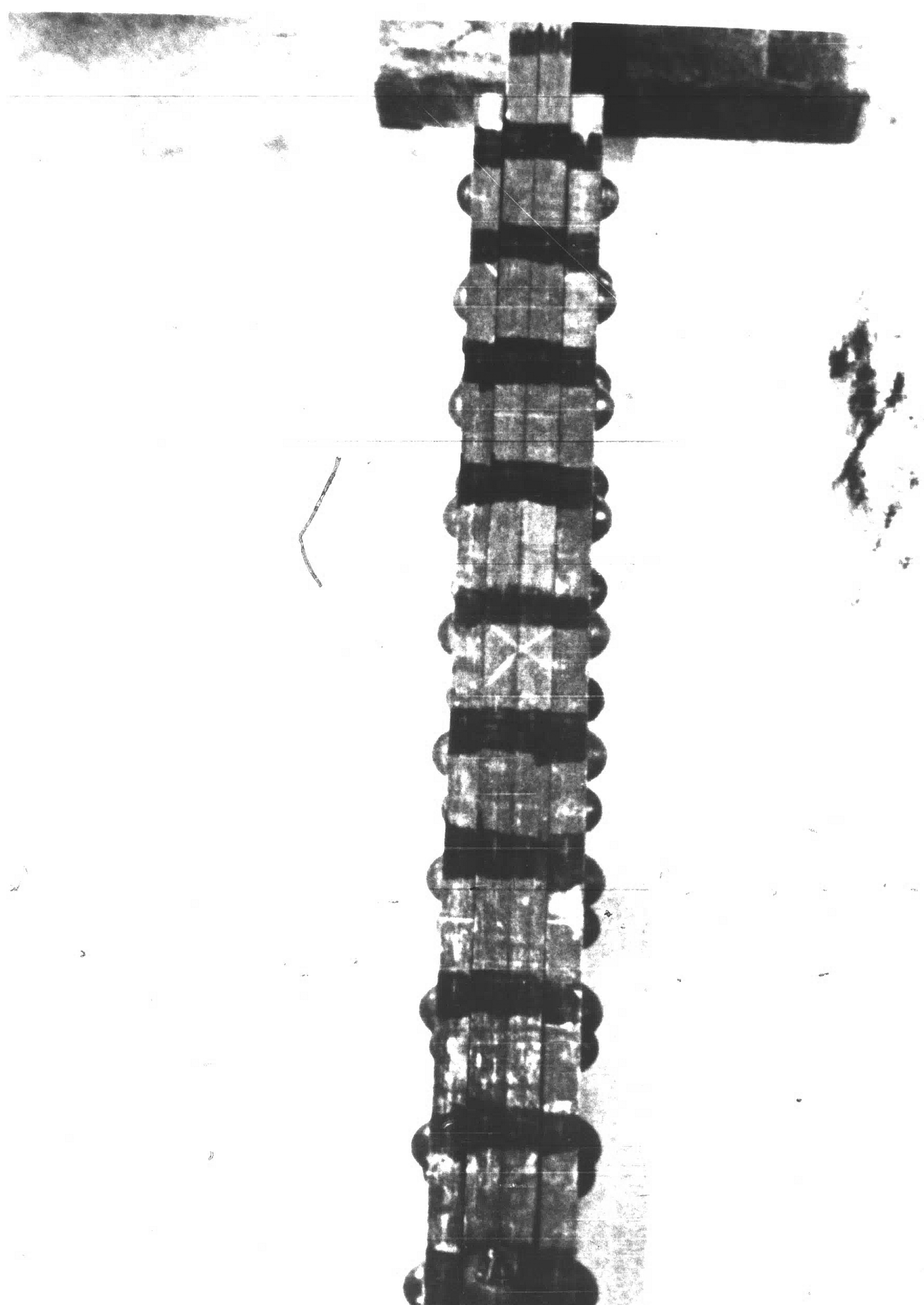


FIG. 8 EDGE VIEW OF JOINT DR 101 AFTER TOP RIVETS SHEARED

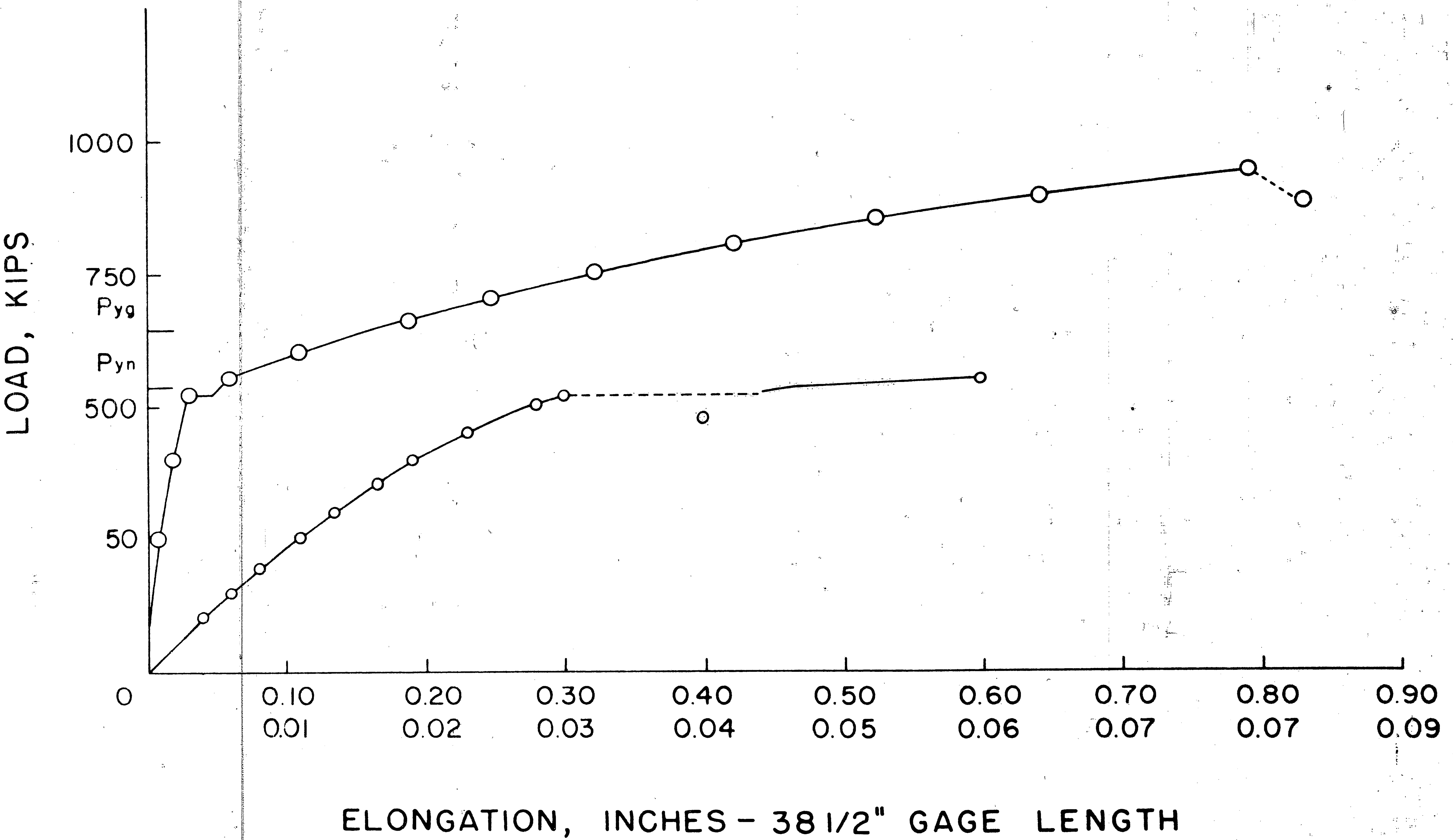


FIG. 9. LOAD-ELONGATION CURVE FOR JOINT DR 101

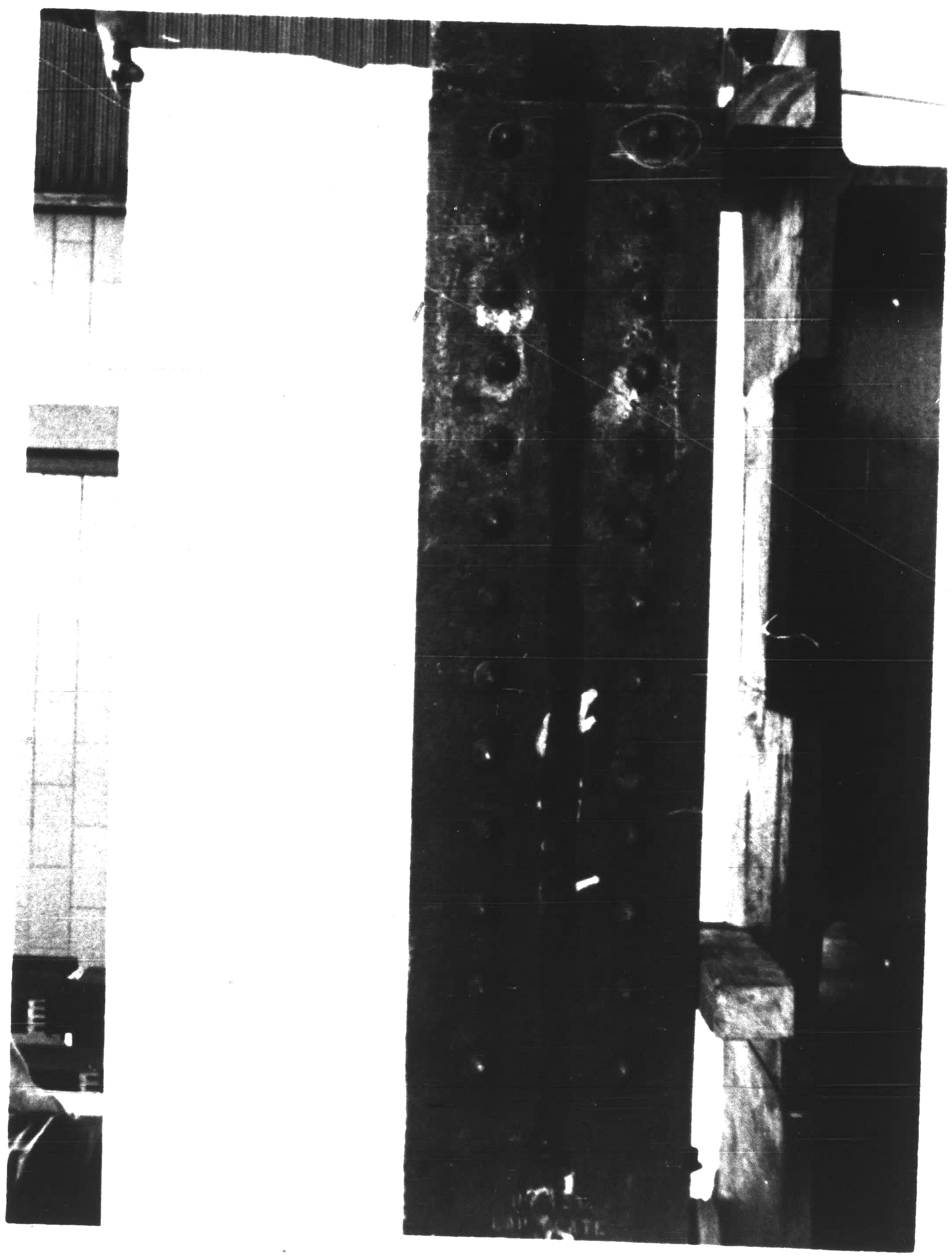


FIG. 10 OVERALL VIEW OF JOINT DR 131
AFTER TOP RIVET SHEARED

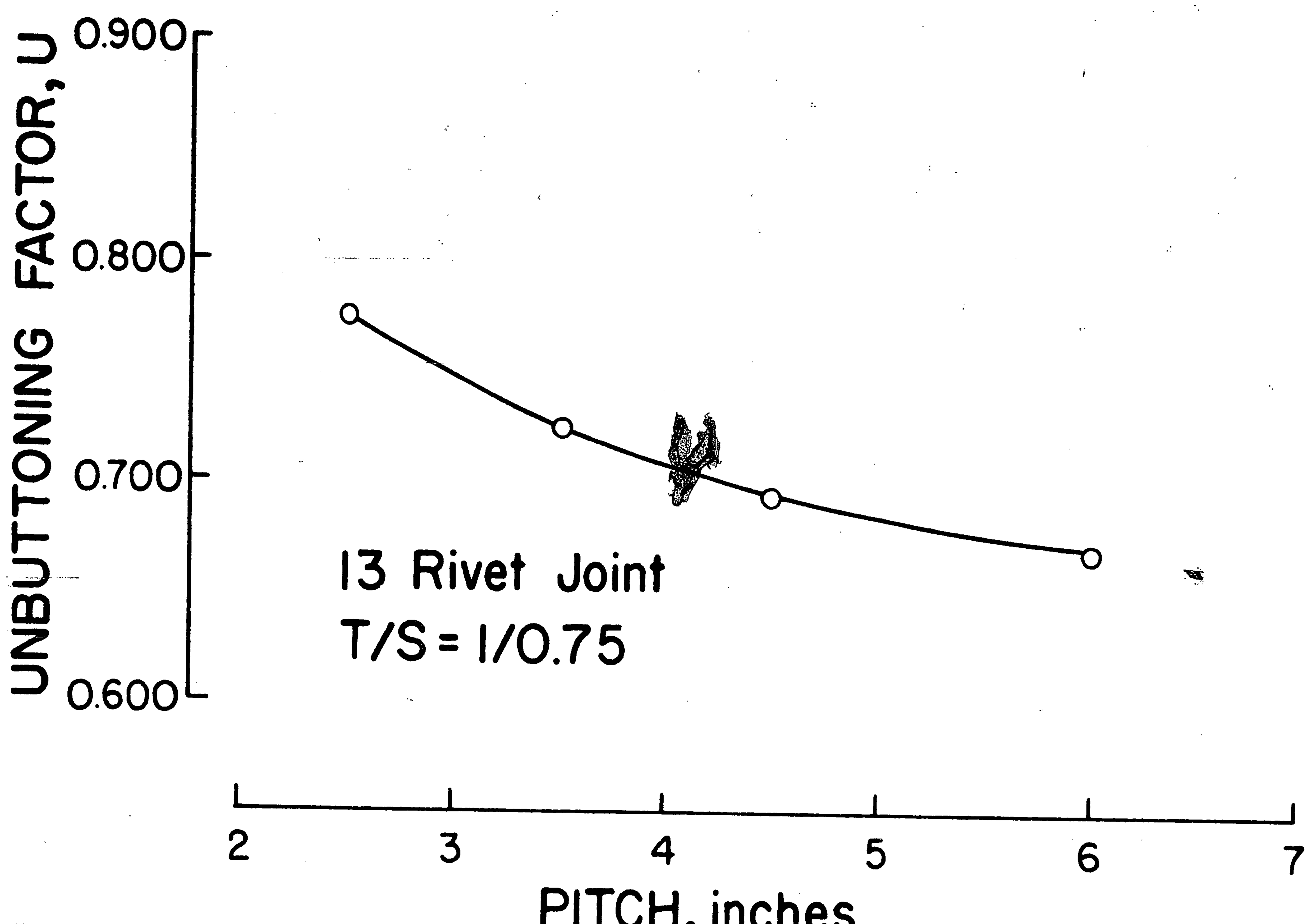


FIG. 11 EFFECT OF PITCH ON THE UNBUTTONING FACTOR

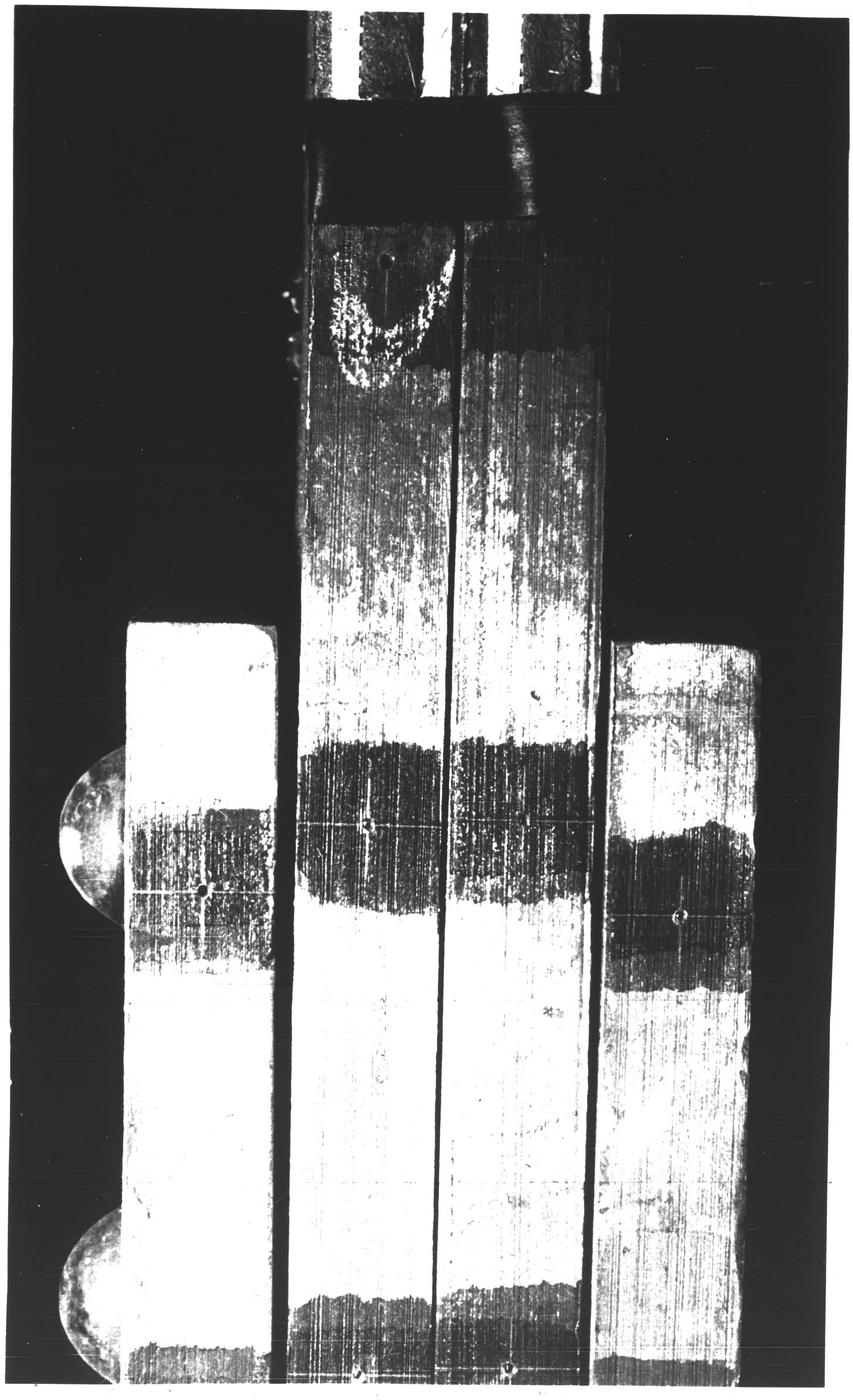


FIG. 12 JOINT DR 131 SHOWING BENDING OUT OF FREE END OF LAP PLATES

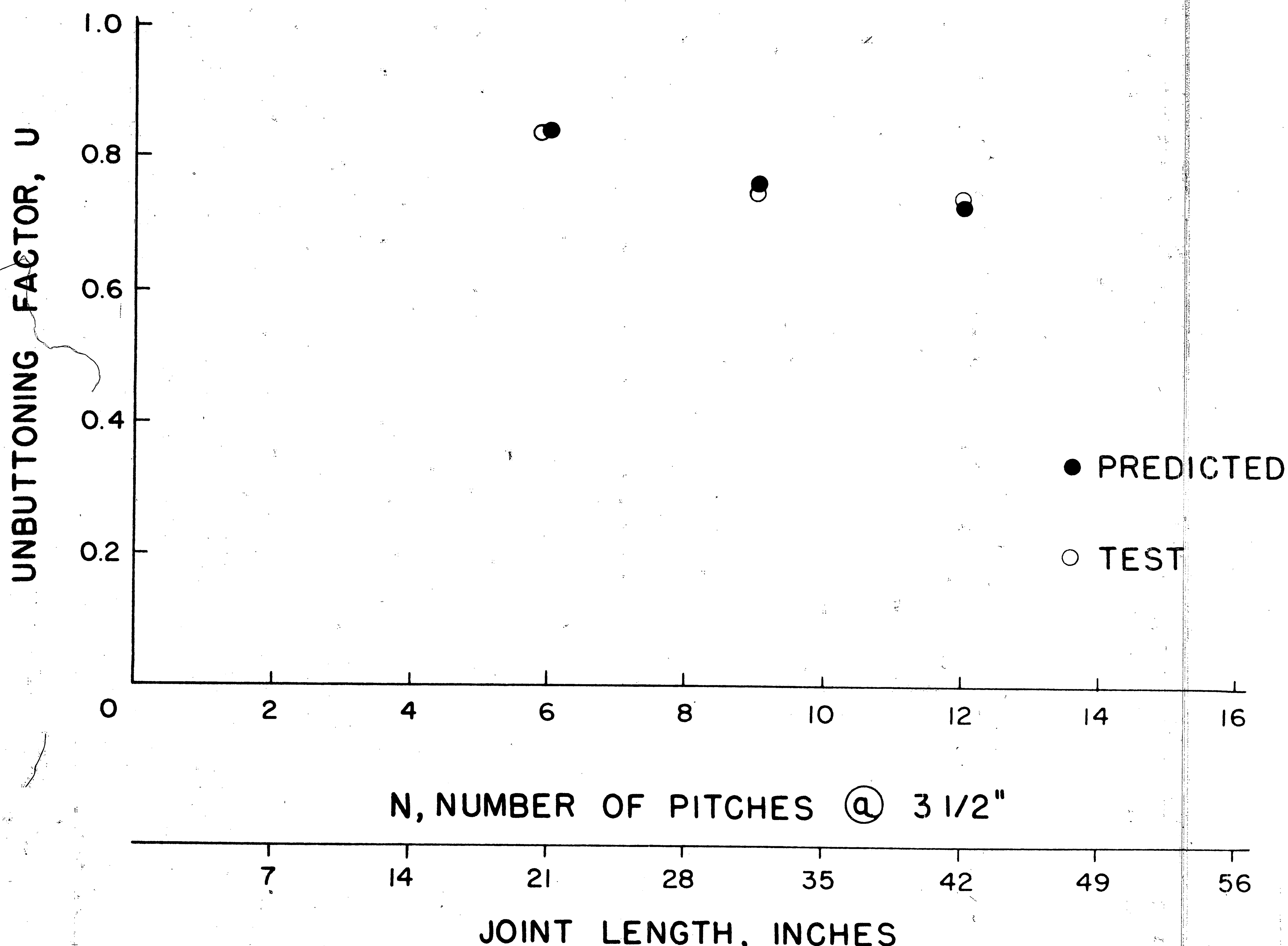


FIG. 13. UNBUTTONING CURVE PREDICTED VS. TEST (DR SERIES)

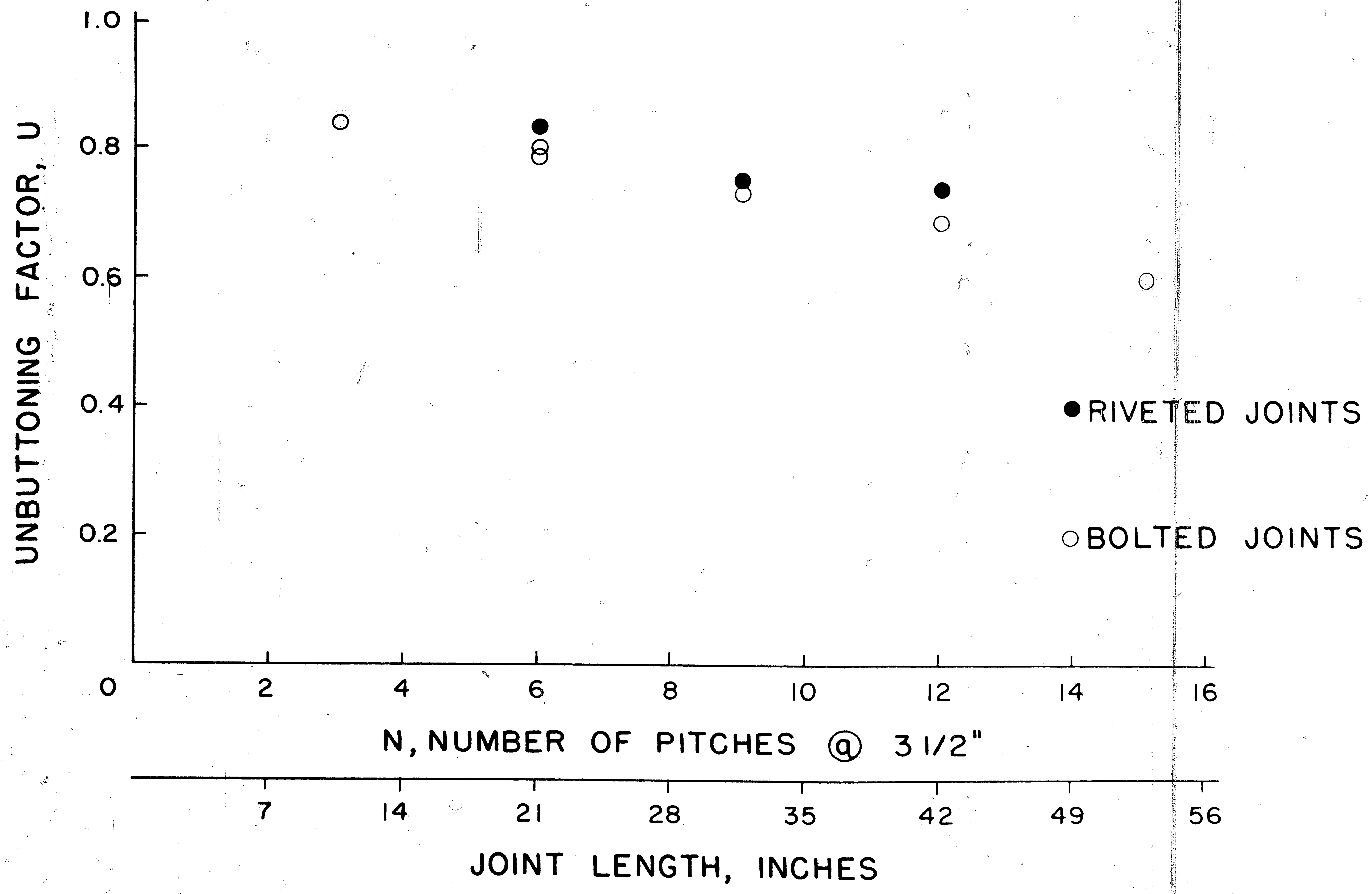


FIG. 14. UNBUTTONING CURVE - TESTS OF DR SERIES VS. TESTS OF BOLTED JOINTS

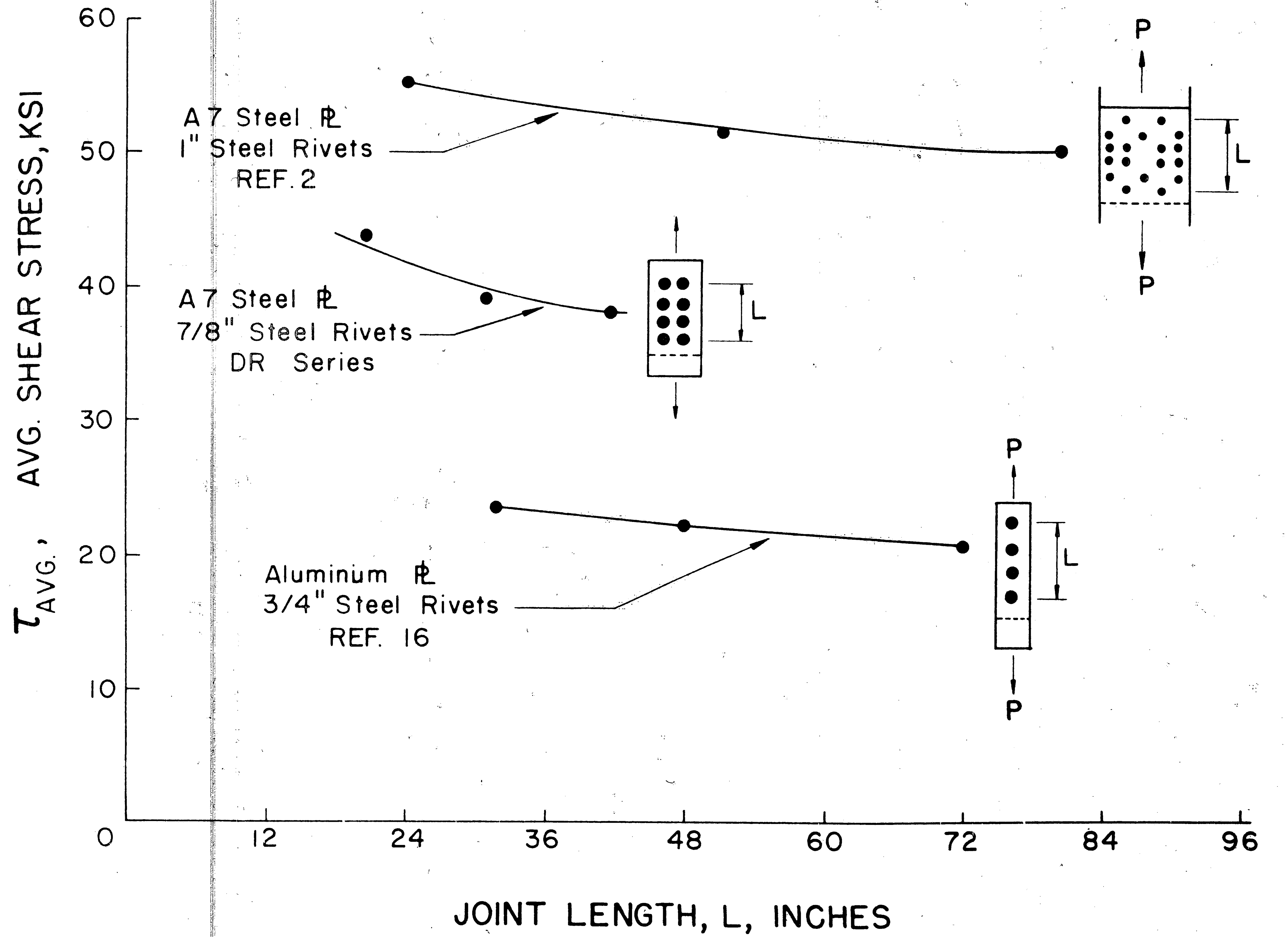


FIG. 15. EFFECT OF JOINT LENGTH

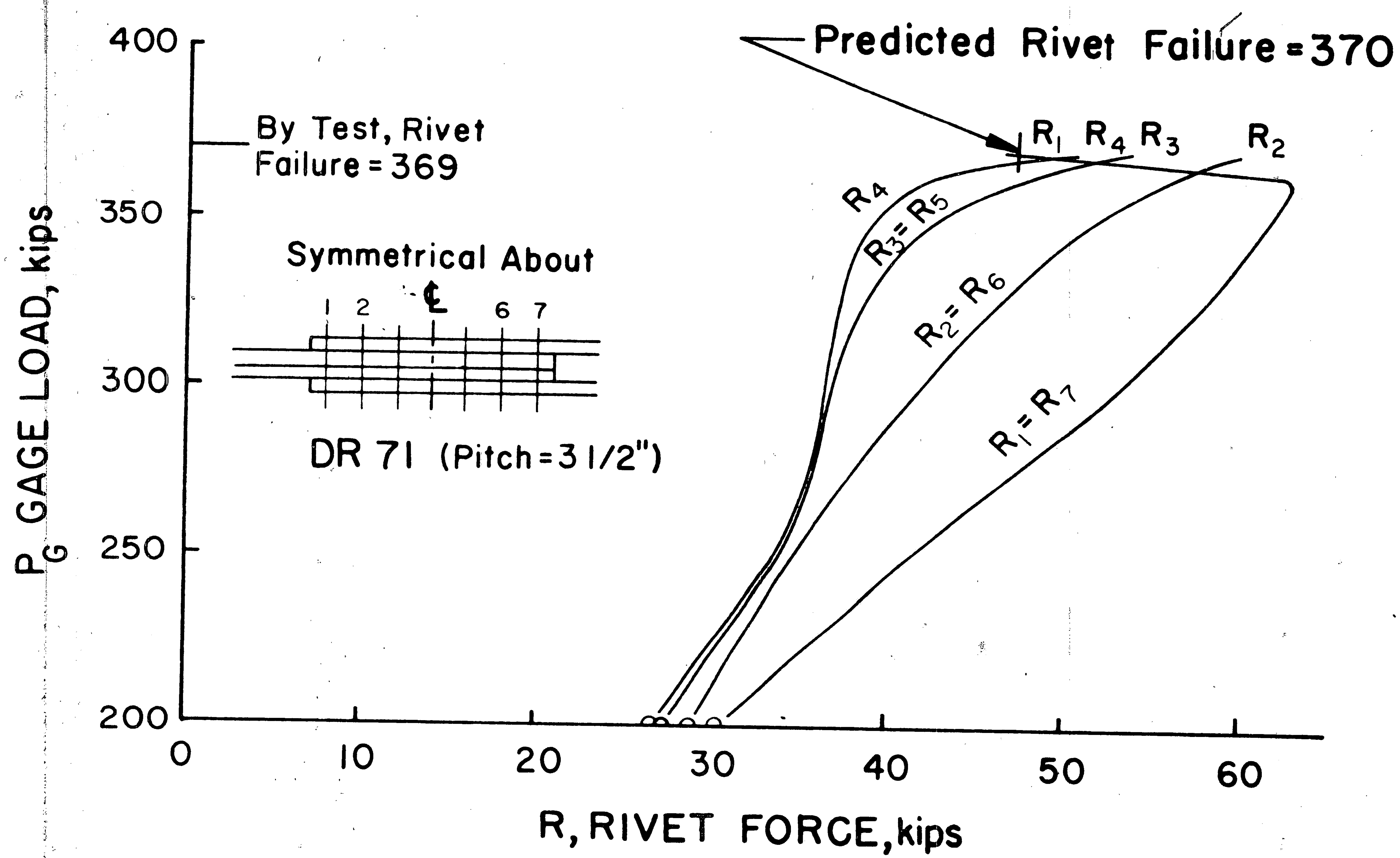


FIG. 16 JOINT DR 71, THEORETICAL RIVET FORCES

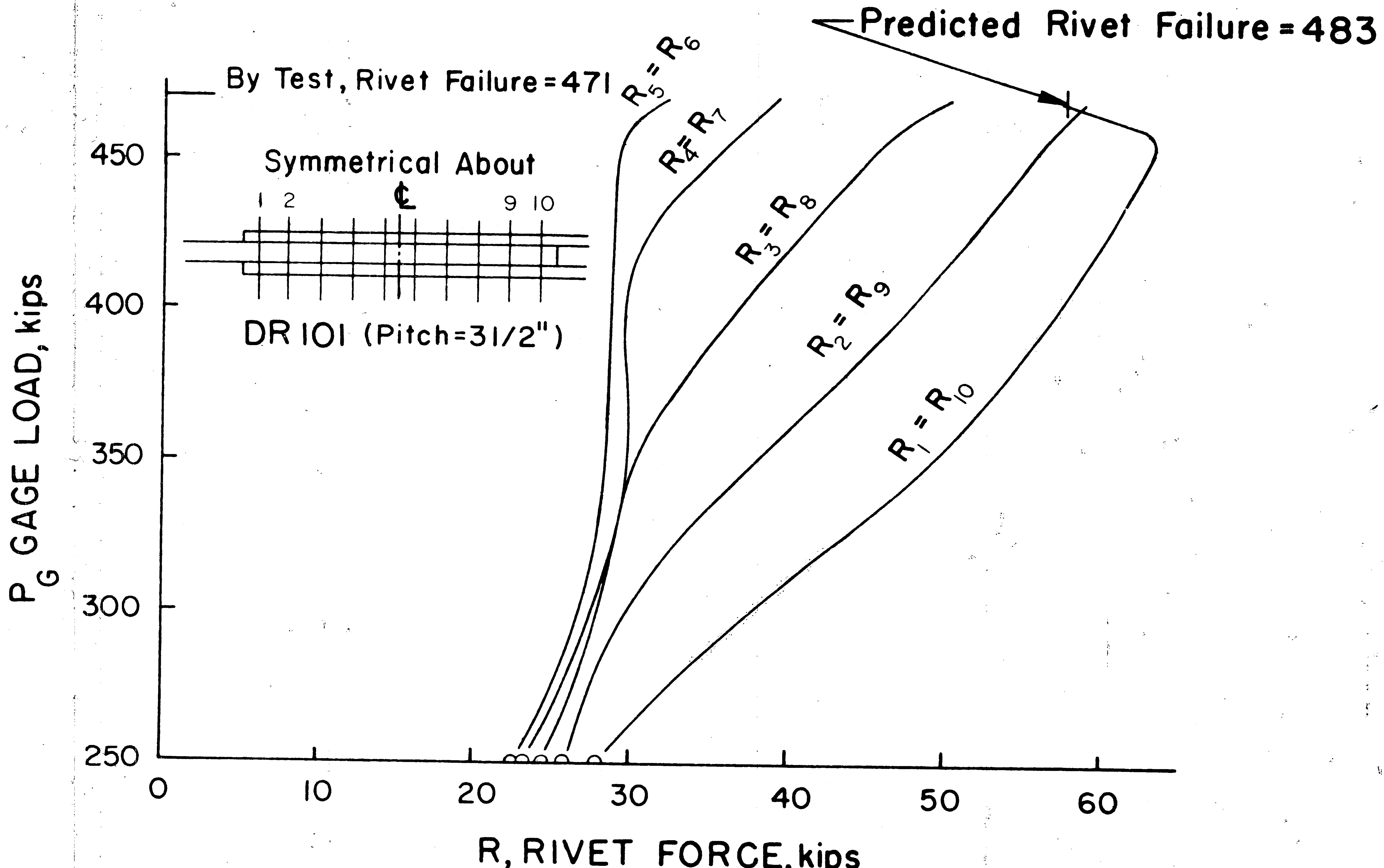


FIG. 17 JOINT DR 101, THEORETICAL RIVET FORCES

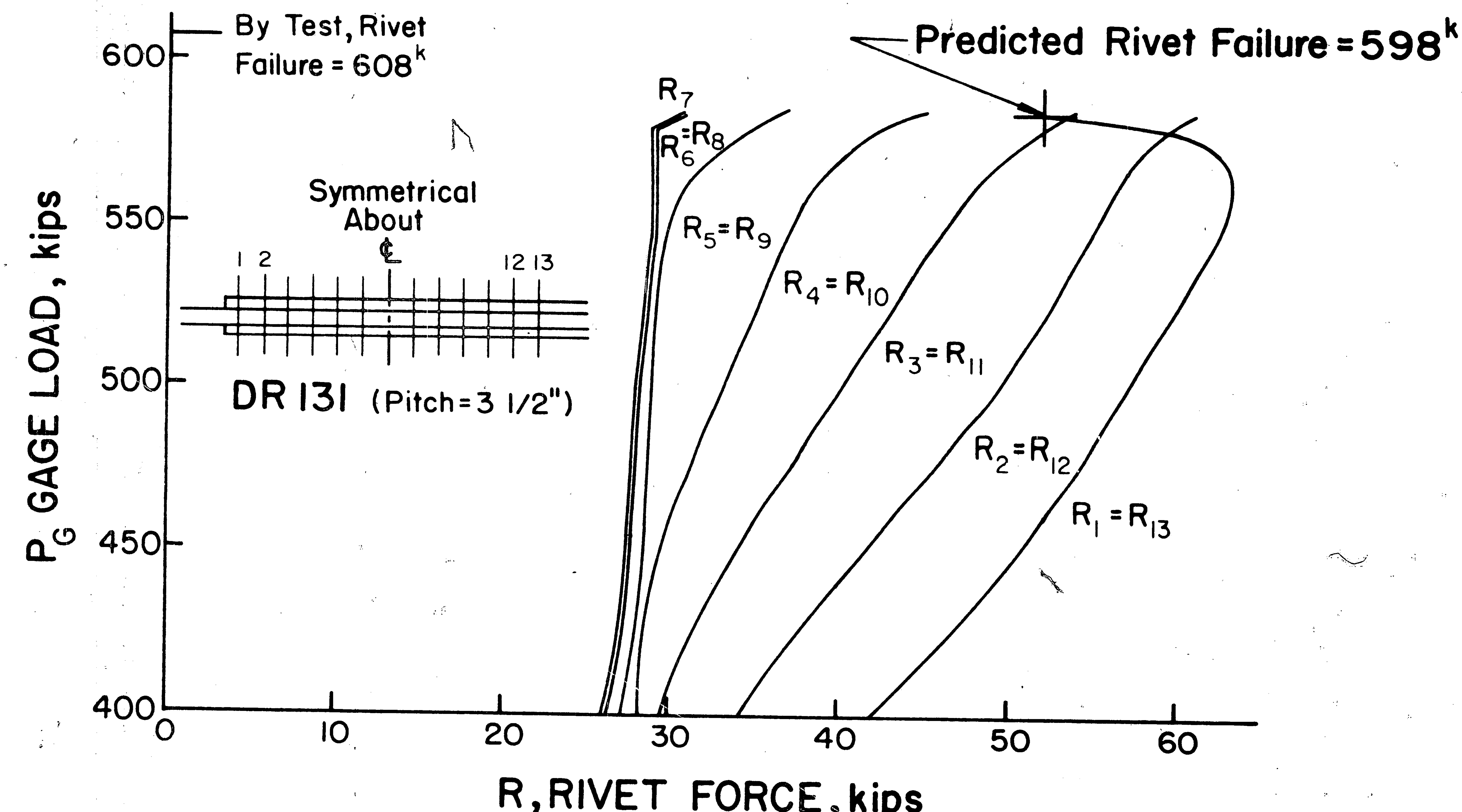


FIG. 18 JOINT DR 131, THEORETICAL RIVET FORCES

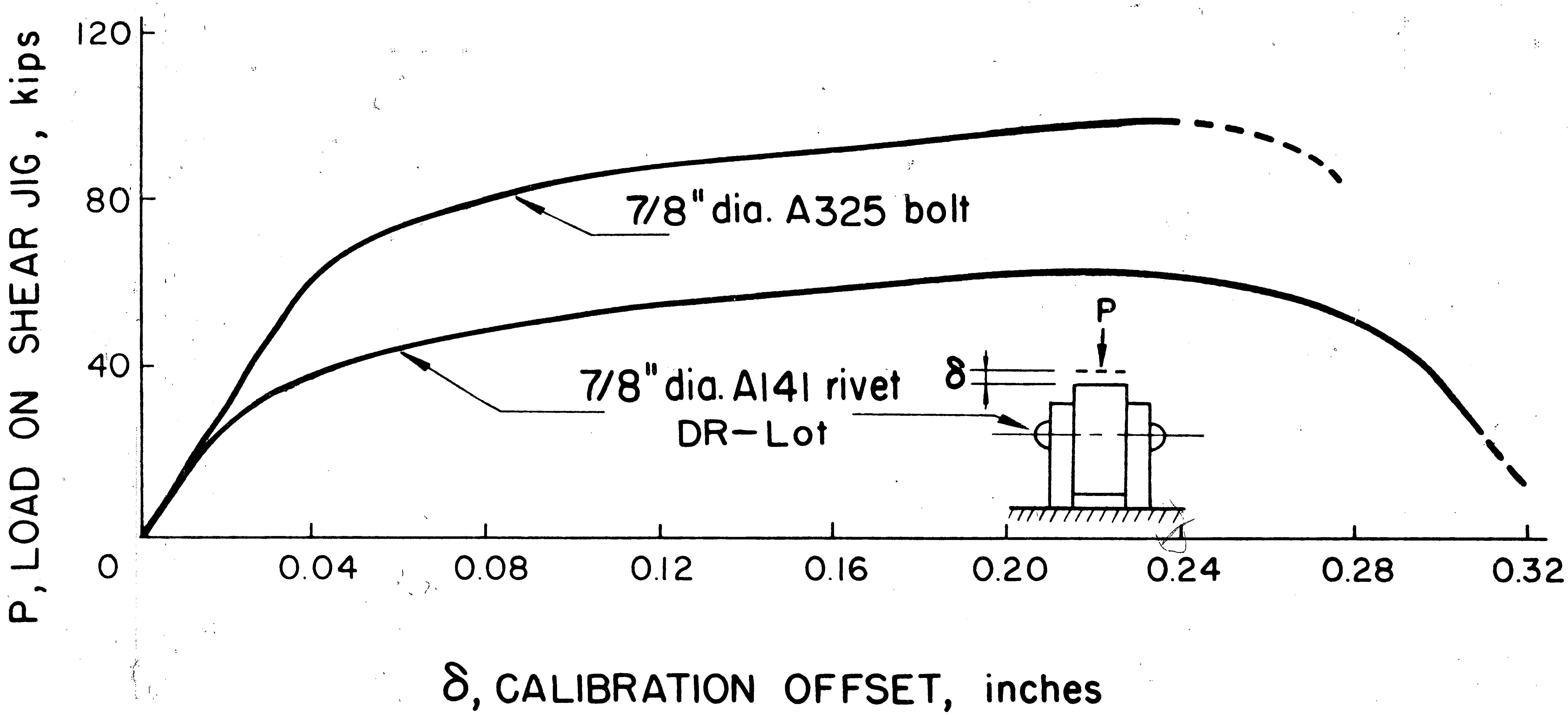


FIG. 19 AVERAGE RIVET AND A325 BOLT SHEAR CALIBRATION CURVES

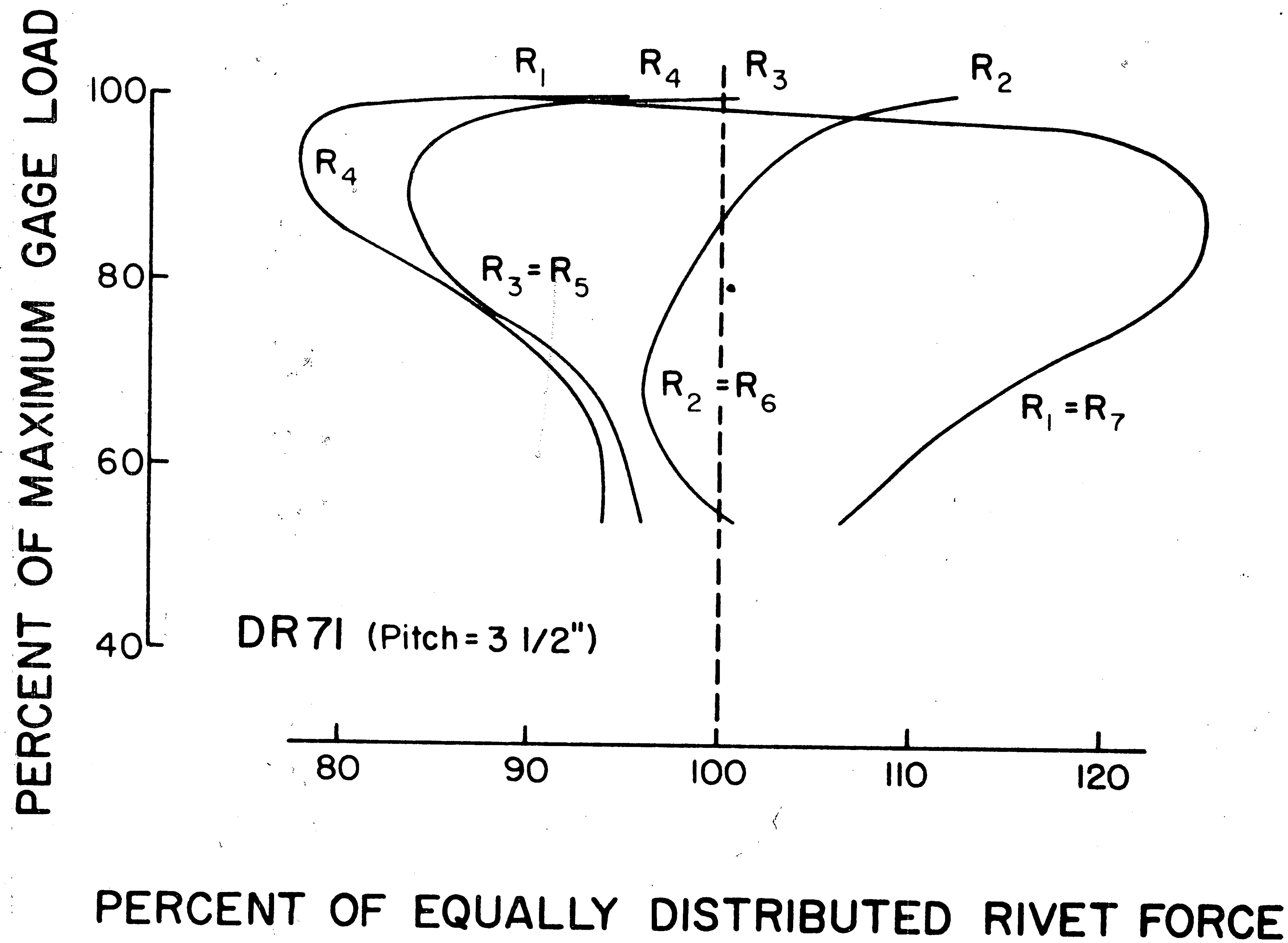


FIG. 20 DR 71 RIVET FORCE DISTRIBUTION

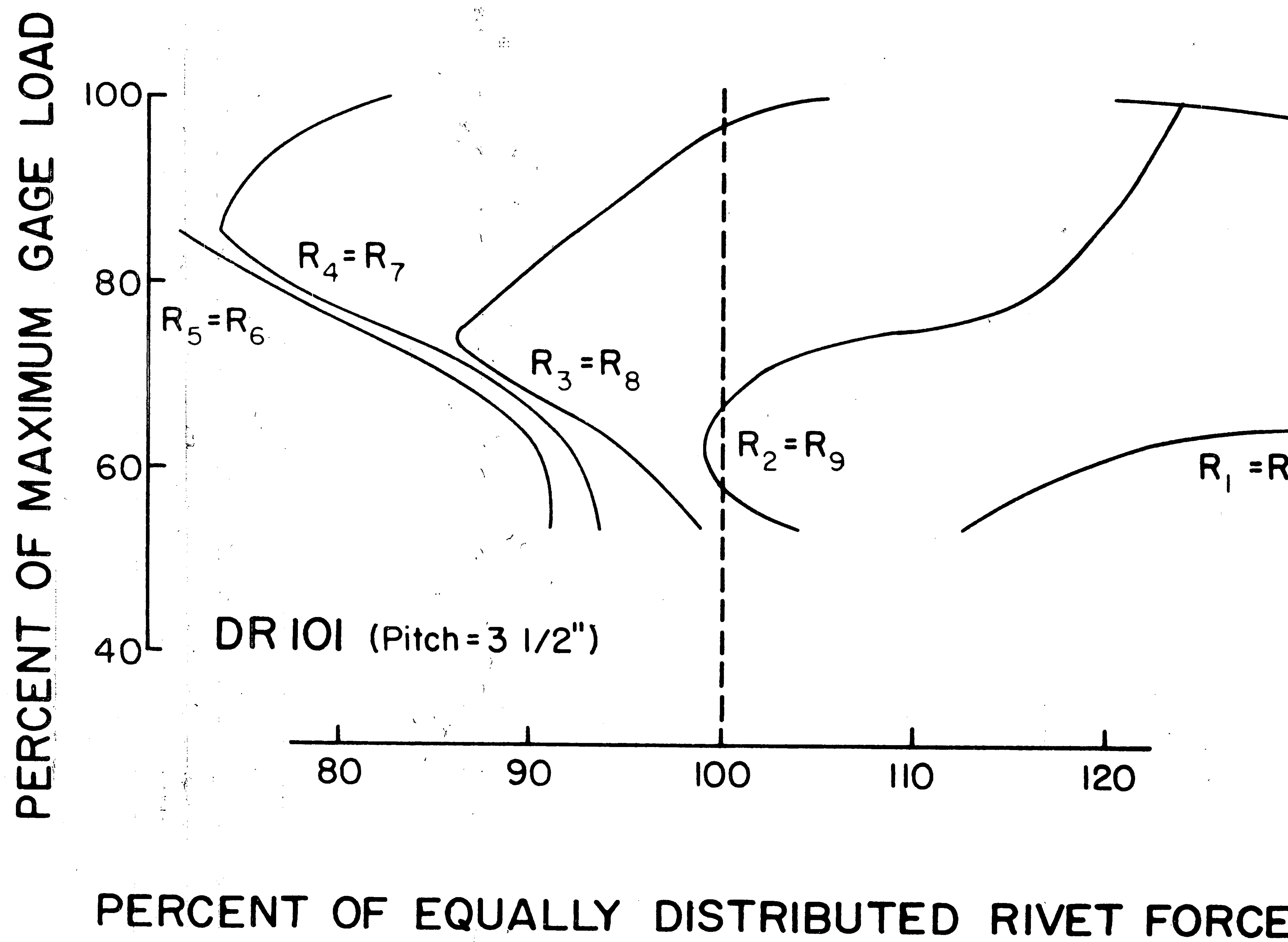


FIG. 21 DR 101 RIVET FORCE DISTRIBUTION

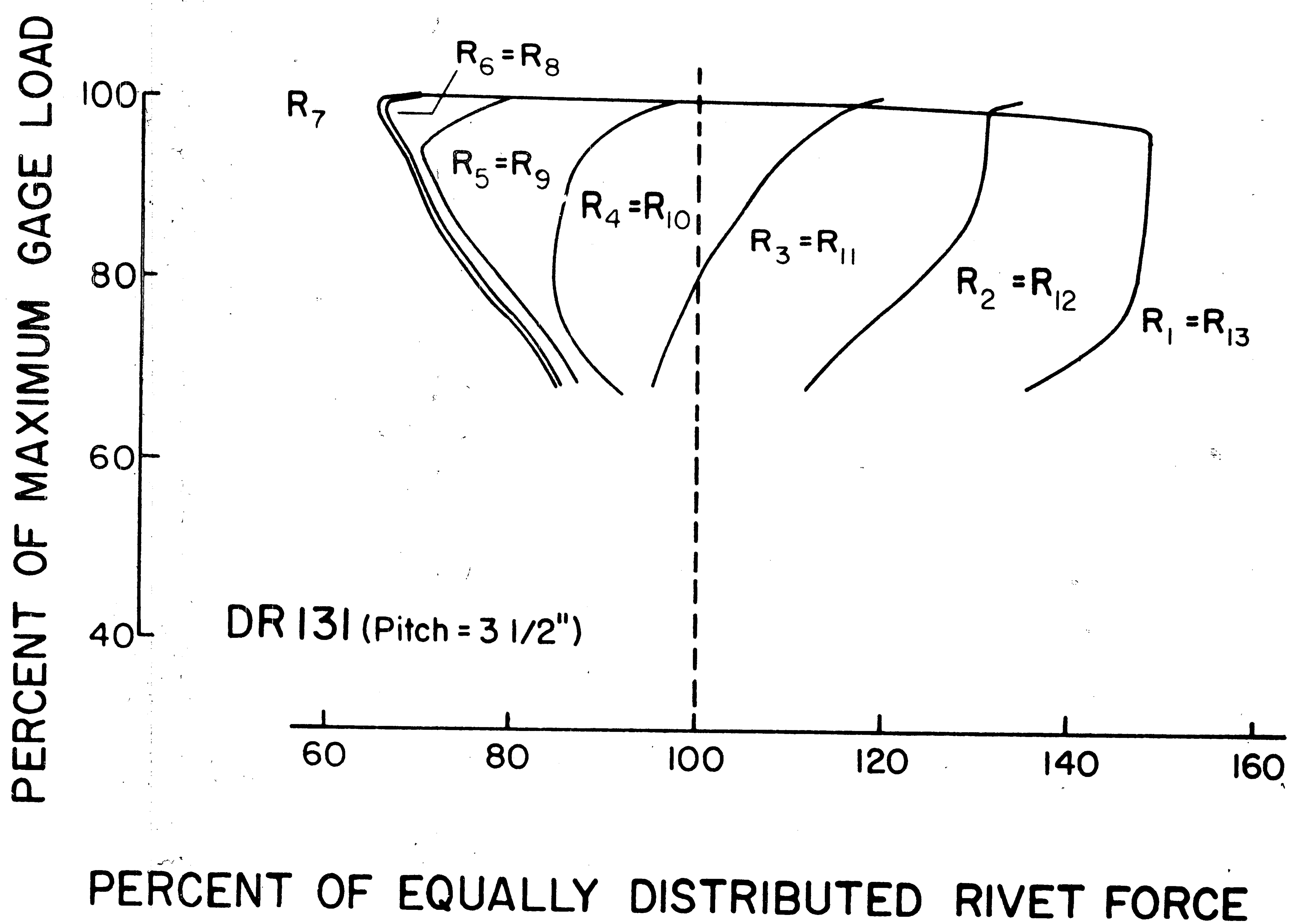


FIG. 22 DR 131 RIVET FORCE DISTRIBUTION

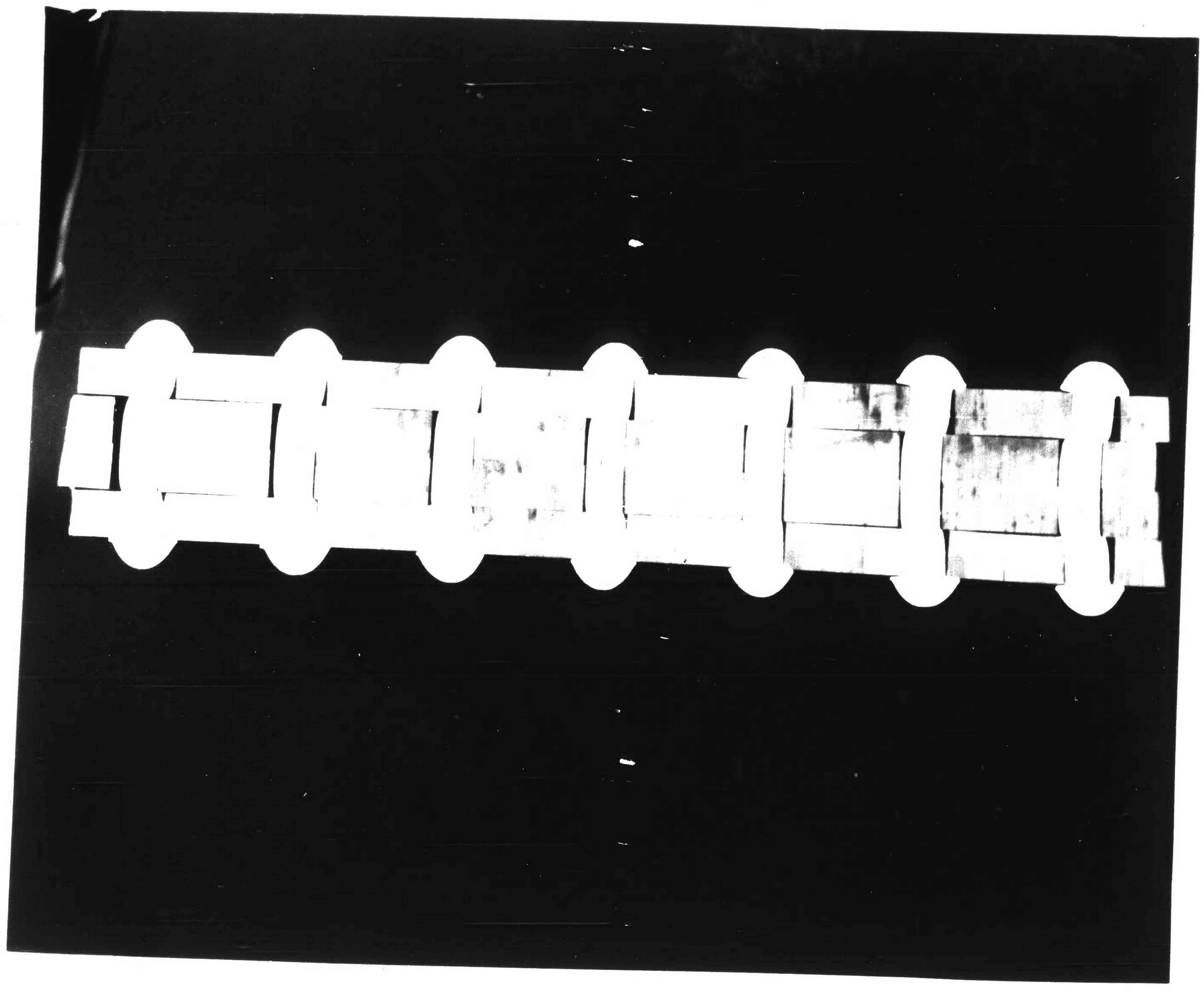


FIG. 23 SAWED SECTION OF JOINT DR 71

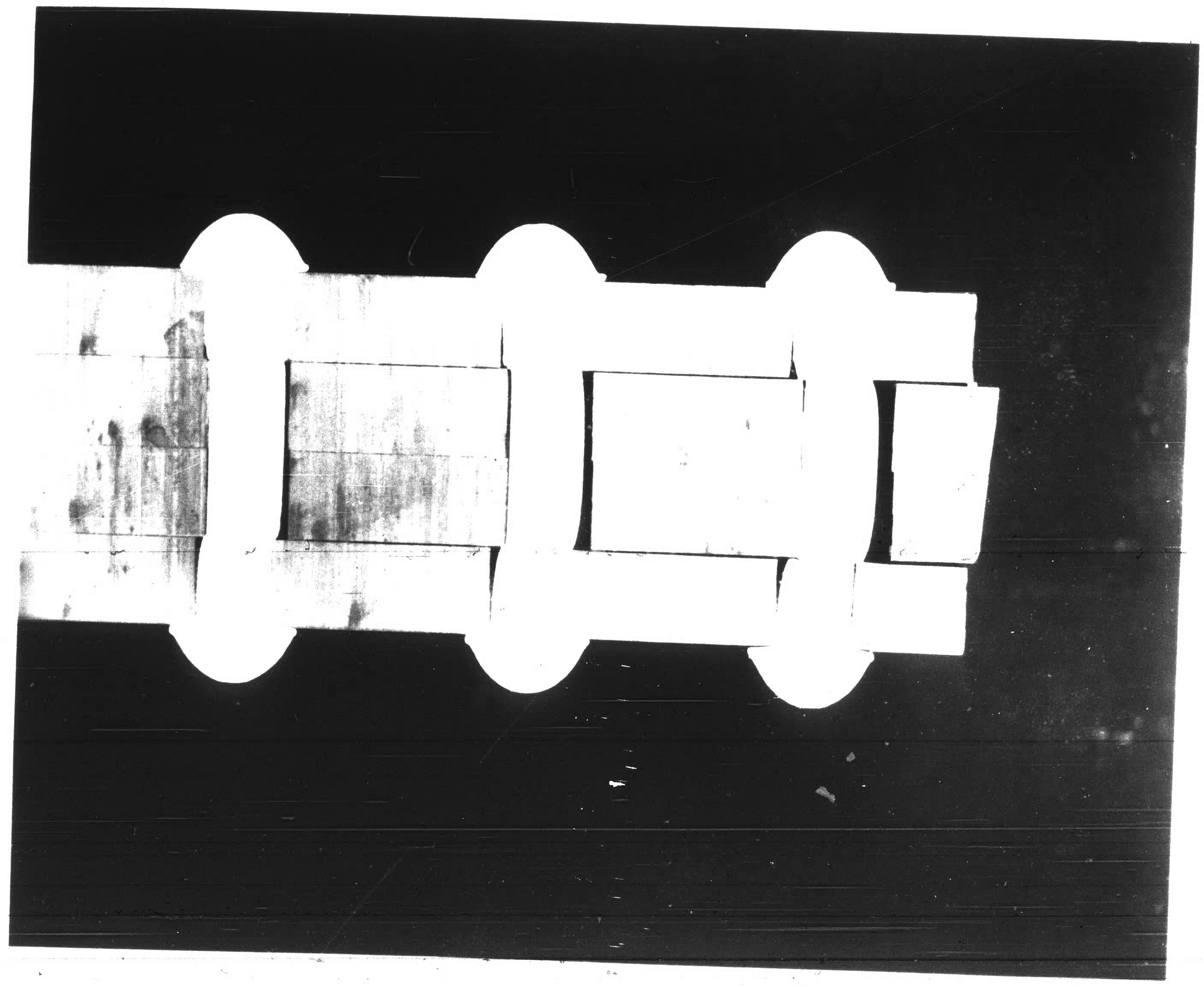


FIG. 24 CLOSE UP OF END RIVET
FROM SAWED SECTION OF JOINT DR 71

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